

Wearability, Comfort and Field of View Findings from the Integrated Launch Suit Test

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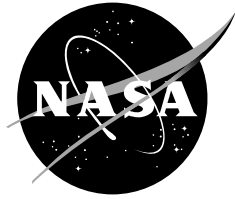
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ABSTRACT

The primary objective of the Launch Suit Test conducted during the period from November 5 to December 9, 2005, was to evaluate crewmember comfort in two planetary suit concepts during 1-g launch conditions similar to those to be experienced in the Crew Exploration Vehicle (CEV). The scope of this report only addresses suit wear in a launch pad configuration; however, the overarching question to be answered is: “Should planetary suits be further considered for launch/entry suits?” The test plan outlined four specific objectives: (1) assess crewmember comfort in the Advanced Crew Escape Suit (ACES), Mark III and the Rear Entry ILC Dover Suit (REI-Suit) in a recumbent position (with helmet); (2) determine the visibility envelope of crewmembers while in the ACES, Mark III, and REI-Suit in a recumbent position (with helmet); (3) determine the ability of crewmembers to sit and stand from a recumbent position unassisted while in the ACES, Mark III, and REI-Suit (with helmet); and (4) determine the reach envelope and motion capability for the ACES, Mark III, and REI-Suit in a recumbent position (with helmet). This report specifically addresses objectives 1 through 3. In summary, the findings of this test support further study of the planetary suit for use as a potential launch/entry suit. The planetary suits evaluated for this test do not increase crewmember discomfort to a level greater than the current ACES and, in some cases, were found to be more comfortable than the ACES. In addition, the field of view was only marginally different in some zones and thus can be considered the same as the ACES. Further study is required to address limitations of this evaluation in addition to addressing other 1-g environments in which a launch/entry suit will be used (e.g., emergency egress).

1.0 INTRODUCTION

The purpose of the Launch Suit Test was to assist in determining the feasibility of using a planetary suit for launch. During this test, conducted from November 9 to December 5, 2005, the Usability Testing and Analysis Facility (UTAF) laboratory was responsible for collecting data that would assist in assessing comfort of planetary suits in a 1-g launch position. The knowledge gained from this test may impact the decision of suit use and design on the initial Crew Exploration Vehicle (CEV) flight, aid any pending CEV suit contract proposal work, as well as provide captured data for the CEV System Requirements Review (SRR). In addition, information would be fed back to the crew consensus on wearability of a planetary suit in the launch configuration.

2.0 OBJECTIVES

The primary objective of the Launch Suit Test was to evaluate crewmember comfort in the planetary suit concepts during 1-g launch conditions in a space vehicle such as the CEV. The scope of this report only addresses suit wear in a launch pad configuration. As outlined in Table 1, other launch elements still need to be addressed. Therefore, the results of this test should not be generalized to these other areas.

Table 1: Launch Suit Elements

1-g Launch Elements	Report Addresses
Ingress	<input type="checkbox"/>
Pad hold time	<input checked="" type="checkbox"/>
Egress (pre/post flight)	<input type="checkbox"/>
Emergency egress (self/assisted)	<input type="checkbox"/>
Ascent	<input type="checkbox"/>
Entry	<input type="checkbox"/>

In addition to evaluating the current planetary suit concepts (Mark III and the Rear Entry ILC Dover Suit [REI-Suit]), the test also included the Advanced Crew Escape Suit (ACES) to provide a baseline for comparative analysis. The ACES design is currently certified and worn in the Space Shuttle Program to protect for a cabin depressurization situation during launch and entry. These three suits represent fundamentally different pressure garment design practices and, thus, testing of all three offered substantial insight into the benefits and problems each offers in this particular environment.

Launch suit mobility range (as evaluated by SF3's Anthropometrics Biomechanics Facility [ABF] laboratory) and visibility data (as evaluated by the UTAf laboratory) requirements were necessary to meet the projected CEV cockpit needs and thus were included as secondary objectives for this test. Table 2 outlines the four objectives evaluated during this test, per AH&I Launch Suit Test Requirements and Test Plan Document (TRD/TPD).

Table 2: Launch Suit Test Objectives (per TRD/TPD)

Objective #	Objective	SF3 Lab
Objective 1	Assess crewmember comfort in the ACES, Mark III, and REI-Suit in a recumbent position (with helmet).	UTAF
Objective 2	Determine the visibility envelope of crewmembers while in the ACES, Mark III, and REI-Suit in a recumbent position (with helmet).	UTAF
Objective 3	Determine the ability of crewmembers to sit and stand from a recumbent position unassisted while in the ACES, Mark III, and REI-Suit (with helmet).	UTAF
Objective 4	Determine the reach envelope and motion capability for the ACES, Mark III, and REI-Suit in a recumbent position (with helmet).	ABF

The UTAF laboratory evaluated objectives 1 through 3 using several different means. The ABF laboratory evaluated objective 4 which will be discussed in report entitled: **Range of Motion Related to Comfort from the Integrated Launch Suit Test Results**. For the purpose of this report, objectives 1 through 3 will be discussed individually along with the findings and conclusions directly related to that objective. A summary section will address the overarching question: “Can a planetary suit be used as a launch suit?” This section will discuss the overall findings along with recommendations for future integrated tests which will allow for a fuller answer to the question.

3.0 TEST LIMITATIONS

Table 3 provides a list of the study limitations for this test. Results of this test should be understood in light of these limitations.

Table 3: Study Limitations

Category	Number	Limitation
Participants	1	A small sample (e.g., 4 crewmembers) was used for this test.
	2	The sample of four crewmembers is not necessarily representative of the entire crewmember core in terms of gender, anthropometric size, or other physical characteristics.
Experimental Configuration	3	The seat used in this test is a mock-up and therefore only allows one to draw conclusions regarding suit comfort in a reclined position. An actual seat may afford the crewmember additional comfort factors (e.g., arm rests).
	4	The suits used for this test are not the actual suits that may be used for the exploration mission. However, they are representative of the types of suits one would expect as possible suit designs.
	5	Only 1-g pad hold time operations were considered in this evaluation. Further testing would be required to access other phases of operation.
Experimental Method	6	Consistent methods were not used for each participant (e.g., each subject did not follow the protocol).
	7	Outside observers engaged with the participant during testing without any consideration for the testing protocol.
Measurement Techniques	8	The field of view technique used is a good approximation and allows for comparative analysis. However, the measurements should not be used for display and control design layouts as it does not provide an accurate measurement of actual field of view.

4.0 TEST CONDITIONS

The TRD/TPD outlines the details of the actual test. This section briefly reviews the test conditions to provide a contextual environment for the reading of this report. While representative of the actual test conditions, full details can be found in the TRD/TPD.

4.1 Test Task Overview

To evaluate the ability of planetary suits to be used for launch suits, crewmembers were asked to sit in a recumbent seat similar to the envisioned launch posture for CEV. Each of the four crewmembers wore each of the three suits, as discussed earlier, on three separate days. In all cases, the ACES was the first of the three suits to be evaluated.

On the day of the test, crewmembers donned the suit, were pressurized and then sat in the recumbent seat. The crewmember was in the pressurized state for a total of 20 minutes. At the end of the 20-minute period, the crewmember's suit was depressurized while still in the seated position. Crewmembers then remained in this position for an additional 100 minutes, for a total of 120 minutes in the recumbent seat. During each of the test conditions, subjects were queried for data relevant to this test (e.g., discomfort, field of view) as will be discussed in detail later.

4.2 Launch Posture

The Launch Suit Test used a recumbent seat for the launch condition. The seat was a simplistic design with adjustable points to position the feet and angle of the hip region to accommodate various sizes of individuals. Although the seat was adjustable, it was not simple to readjust the seat and thus only one seat configuration was used for all participants without adjustment for different anthropometric sizes. Figure 1 provides a picture of the actual seat used with a participant wearing the ACES in the recumbent position.

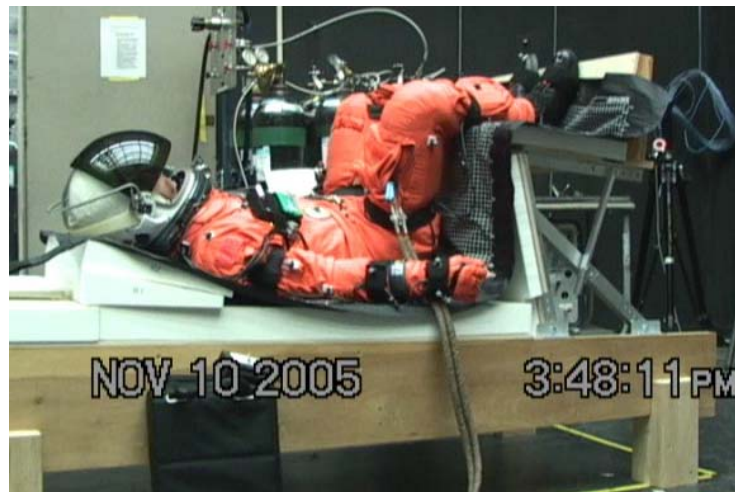


Figure 1: Launch Seat Configuration

4.3 Test Suits

Three suits were used for the Launch Suit Test: ACES, Mark III, and REI-Suit. Each suit will be briefly discussed. Figure 2 provides a picture of each suit.

4.3.1 ACES

The ACES is designed to provide protection to each crewmember for the following conditions: (1) loss of cabin pressure; (2) environmental extremes; (3) effects of prolonged zero gravity; and, (4) contaminated atmosphere. The ACES is a full pressure suit that applies static pressure evenly to the entire body surface. This pressure is maintained by a dual suit controller and, at full inflation, provides an absolute pressure of 3.67 psia to a crewmember's body. A pressure demand regulator located at the rear of the neck ring delivers positive pressure inside the helmet to protect the crewmember up to an altitude of 100,000 feet. The ACES has an inner pressure bladder that encompasses the crewmembers body and an outer covering. The pressure bladder is constructed of Gore-Tex material that wicks body moisture and vapor away from the crewmember when unpressurized, yet holds pressure when inflated. The outer covering is made of orange Nomex material that is heat/flame resistant and provides a highly visible target for Search and Rescue (SAR).

For this Launch Suit Test, subjects wore the lightweight or expedition weight underwear, cooling garment, ACES coverall, gloves, and helmet. The anti-g-suit (unpressurized) and harness (includes life preserver and oxygen system) were excluded from the suit configuration because it was deemed that they would not be needed in the proposed CEV configuration in the same form as provided in the current ACES. In addition, the Personal Parachute Assembly (PPA) was excluded since there is no clear requirement for a parachute supported bailout for CEV, and the PPA essentially creates a large mass between the subject and the seat.

4.3.2 Mark III

The Mark III represents a hybrid space suit configuration composed of hard elements such as a hard upper torso and hard brief section along with soft components such as the fabric elbows and knees. The Mark III uses bearings in multi-axial mobility joint systems at the shoulder, upper arm, waist, upper hip, mid hip, upper leg (3 bearing hip), and ankle joints. The suit is entered through a hatch on the backside of the hard upper torso (rear entry suit) that also accommodates integration of a backpack. Suit subjects are integrated to the suit by a waist belt weight relief system and shoulder straps. The boots of the suit are modified commercial work boots with flexible soles for walking and convolute ankle joint for mobility. The Mark III weighs approximately 120 pounds. Sizing features consist of modular sized leg, arm, and boot soft goods components. Fine sizing adjustments are made with metal sizing rings. The suit torso and waist/hip structures were designed for the 95% sized male anthropometric measurements so that the greatest number of test subjects could be accommodated. To improve the indexing of the smaller test subjects to the suit and to provide weight relief off of the shoulder for all subjects, an internal weight relief system (waist belt) is incorporated in the suit. In addition to the suit, the Mark III has its own Liquid Cooling Garment (LCG). For this test, the Mark III's LCG was used when wearing the suit.

4.3.3 REI-Suit

The REI-Suit is primarily a soft suit, incorporating a limited number of bearings at the shoulder, upper arm, upper hip, and upper leg (2 bearing hip) joints. The suit represents a compromise between a hard/hybrid suit and a soft suit such as the Apollo A7LB Suit. The boots are the lower portion of an off-the-shelf work boot incorporating a patterned convolute ankle joint for mobility. The boot also incorporates air bladders that can be pumped up to anchor various sized feet in the boot. The suit incorporates a rear-entry body seal closure and a rigid frame for backpack integration. The REI-Suit weighs approximately 80 pounds. Sizing features include axial restraint loops, incorporating ¼" bracket adjustments and a range of waist axial restraint lengths. In addition to the suit, the REI-Suit has its own LCG. For this test, the REI-Suit's LCG was used when wearing the suit.

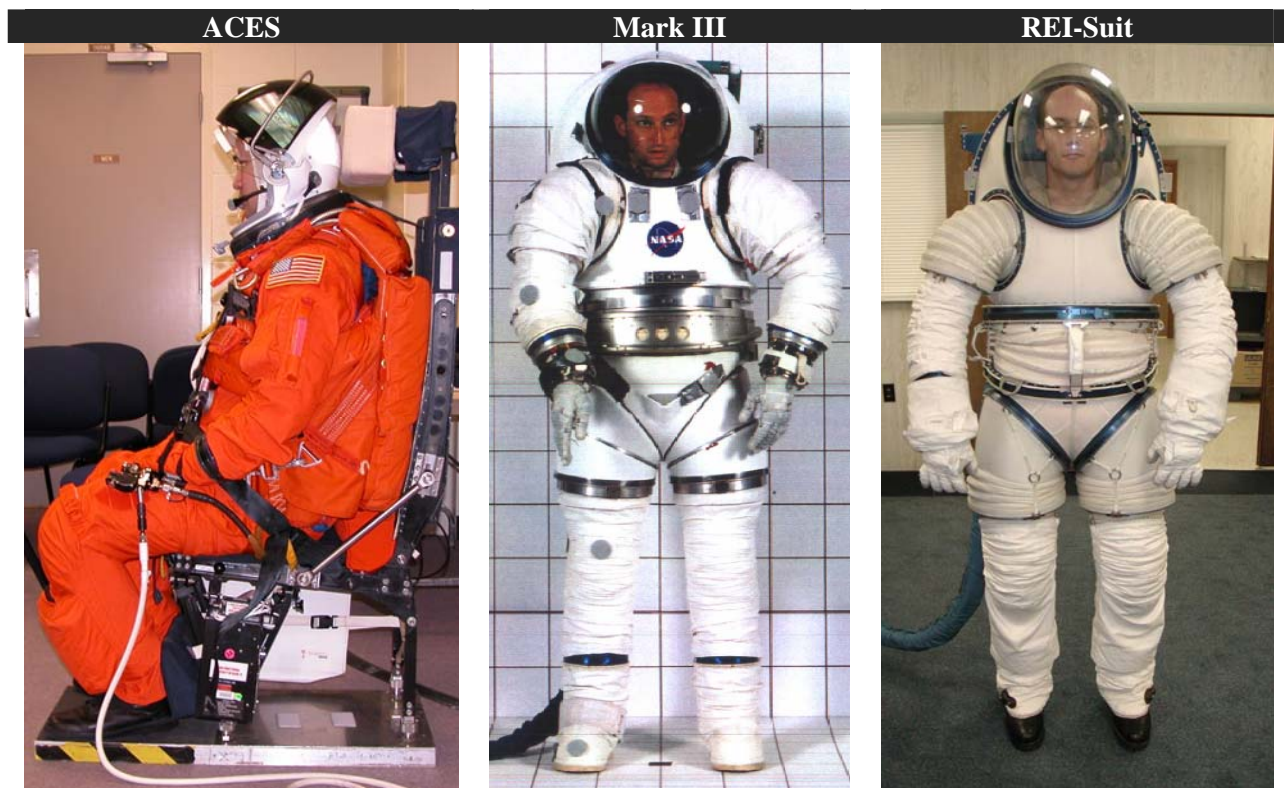


Figure 2: ACES, Mark III, and REI-Suit Test Suits

4.4 Test Participants

The test included a total of six participants: two engineering test participants and four active astronaut participants. The engineering participants were used to evaluate the test configuration and data collection instruments; no data presented within this report was taken from these participants. The four astronauts served as actual test participants during the test. All had shuttle experience and thus were familiar with the ACES. One crewmember was a pilot. None of them had worn the Mark III or REI-Suit extensively beyond the minimum time required to ensure they fit the suits. The astronaut participants do not represent the full scale of crewmember anthropometric sizes within the current astronaut core. In fact, participants were limited to only those that could properly fit within the available development suits (Mark III and REI-Suit). However, for comfort assessment, this was deemed feasible for early testing. Future testing may expand to a broader range of crewmembers.

5.0 HUMAN FACTORS ASSESSMENT RESULTS

To evaluate test objectives 1 through 3, several human factors measures were used for the assessment (see Table 3). Each measure and its use in evaluating a specific objective are discussed below.

Table 4: Human Factors Assessment Measures

Objective	Item Evaluated	Measure	Description
1	Comfort	Holistic Discomfort Questionnaire	Eight self reports in the unpressurized condition and one self report in the pressurized condition. Discomfort questionnaire developed by UTAF.
1	Comfort	Body Discomfort Scale	Five self reports in the unpressurized condition and two self reports in the pressurized condition. Self reported discomfort using scale developed by Corlett and Bishop (1976). This scale is a typical Borg scale used in other human factors measures.
1	Comfort	Mobility Questionnaire	Three self reports in the unpressurized condition and one self report in the pressurized condition. All reports were completed at the conclusion of range of motion evaluations.
2	Visual field of view	Visual Field of View	A modified Goldman perimeter was used to assess field of view.
3	Sit/Stand Ability	Sit/Stand Ability	Observed crewmember ability to sit/stand in unpressurized suit.

5.1 Comfort Assessment – Objective 1

Comfort is typically measured through the absence of discomfort. Four measures of comfort/discomfort were proposed as shown in Table 4. However, only three measures were actually used in this evaluation: holistic discomfort questionnaire, body discomfort assessment, and mobility discomfort questionnaire. A fourth measure, postural shifts, was not used as will be discussed later.

5.1.1 Holistic Discomfort Questionnaire Results

The first measure, a holistic discomfort assessment questionnaire (see Figure 3), asked a participant various questions concerning the discomfort/comfort of the suit and various parts of the suit. This questionnaire was designed to identify what the participant believes is the source of discomfort along with suggestions for improvements to the suit design.

Rate the following:		No Discomfort						Extreme Discomfort
1.	Overall discomfort you feel <u>right now</u> while wearing the suit	1	2	3	4	5	6	7

Please indicate the extent to which the following side effects are present:		None						Extreme	Where?
2.	Itching	1	2	3	4	5	6	7	
3.	Hot Spots (e.g. areas of the suit that are warmer than the rest of your body)	1	2	3	4	5	6	7	
4.	Rub spots (e.g., any areas of the suit that are rubbing you)	1	2	3	4	5	6	7	
5.	Fogging of your face shield	1	2	3	4	5	6	7	N/A
6.	Sweating (general, palm, head)	1	2	3	4	5	6	7	
7.	Nausea	1	2	3	4	5	6	7	N/A
8.	Disorientation (e.g., dizziness)	1	2	3	4	5	6	7	N/A

Rate the following comfort factors of the whole suit:									
									Comments
9.	Snug							Loose	
	1	2	3	4	5	6	7		
10.	Heavy							Lightweight	
	1	2	3	4	5	6	7		
11.	Stiff							Flimsy	
	1	2	3	4	5	6	7		
12.	Statical							Non-statical	
	1	2	3	4	5	6	7		
13.	Slippery							Sticky	
	1	2	3	4	5	6	7		
15.	Absorbent							Nonabsorbent	
	1	2	3	4	5	6	7		
16.	Cold							Hot	
	1	2	3	4	5	6	7		
17.	Dry							Damp	
	1	2	3	4	5	6	7		
18.	Rough							Gentle	
	1	2	3	4	5	6	7		
19.	Smooth							Scratchy	
	1	2	3	4	5	6	7		

Figure 3: Holistic Discomfort Questionnaire

Overall discomfort was assessed through the Likert scale of question 1. Figure 4 shows the responses over time through the two conditions: pressurized and unpressurized. As can be seen, crewmembers experienced some overall level of discomfort in every suit. However, the two planetary suits' (i.e., Mark III, REI-Suit) overall level of discomfort did not seem to differ much from the ACES. In fact, in the pressurized condition, crewmembers reported less discomfort in the planetary suits than in the ACES. One will notice that the discomfort in the ACES during the pressurized condition dramatically increases in the 20-minute period. This discomfort was primarily attributable to the discomfort felt in the back of the knees (i.e., Popliteal Fossa). The crewmembers' discomfort overall in the Mark III and REI-Suit suggests that planetary suit designs can be further evaluated as potential launch/entry suits.

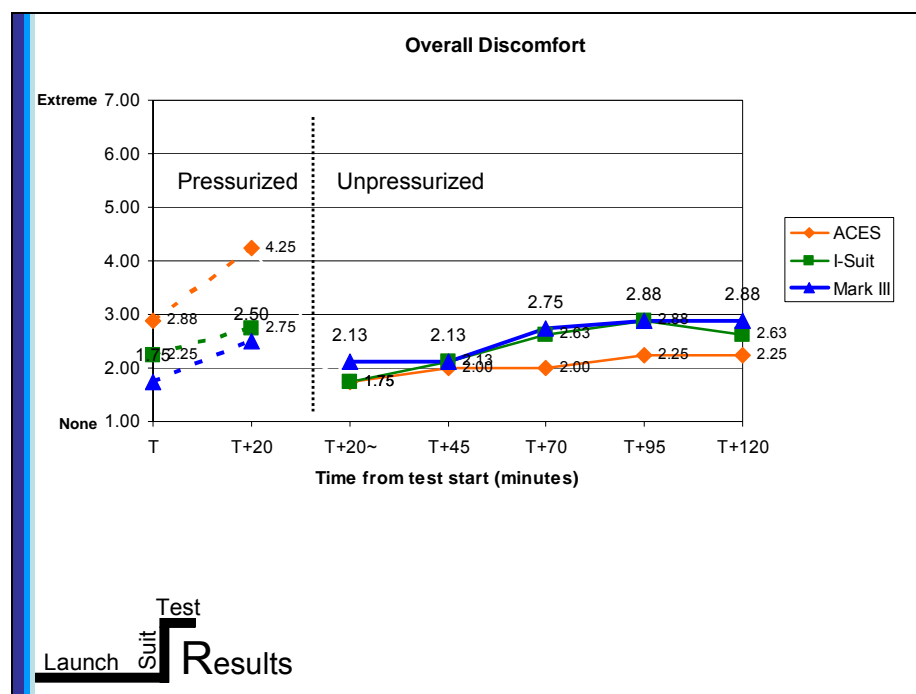


Figure 4: Overall Discomfort

In addition to the overall discomfort, crewmembers were queried about itching, hot spots (temperature), rub spots, helmet fogging, sweating, nausea, and disorientation (see Figure 3, questions 2 through 8). Crewmembers never experienced nausea and disorientation in any of the suits. Helmet fogging was reported in only one instance. For the other discomfort queries (itching, hot spots, rub spots, sweating), no subjective differences were found between the three suits. Appendix 1 shows the details of each measure.

Crewmembers were also queried about the characteristics of the suit that may impact suit comfort. The adjectives used for this portion of the questionnaire were drawn from the clothing comfort literature and have been used successfully since the 1960s to characterize clothing comfort. The Comfort Rating Scale (Hollies, 1965; Hollies et al., 1979; Hollies & Goldman, 1977) uses 15 adjectives to rate the wear of clothing. The rating adjectives were used during the

engineering runs to evaluate the suit comfort. Based on the feedback, the scales were adapted to request crewmembers to evaluate different characteristics of comfort with bipolar adjectives. Crewmembers were asked to rate the suit as to the degree of each bipolar adjective: Snug/Loose, Heavy/Lightweight, Stiff/Flimsy, Statical/Non-statical, Slippery/Sticky, Absorbent/Nonabsorbent, Cold/Hot, Dry/Damp, Rough/Gentle, and Smooth/Scratchy (see Figure 3, questions 9 through 19). The results of each adjective pair are included in Appendix 1. While crewmembers were queried in each condition, as discussed earlier, in general most crewmembers rated the suit once in the pressurized and then again in the unpressurized condition and seldom changed their rating when queried again throughout the test. Thus most of the ratings show a straight line indicating no change to the initial rating. A review of the findings shows little differences between suits. The Dry/Damp adjective is the only one where there is more of a difference. For this adjective pair, the ACES and REI-Suit were found to be more damp than the Mark III. One can only suggest that this is because the ACES and REI-Suit are softer and thus lay closer to the body than the Mark III. Thus any dampness is more likely to be felt by the participant.

The last set of questions in the holistic evaluation asked each crewmember to project their ability to wear the suit for an extended period of time in the particular condition (see Figure 5, questions 20 through 23). Crewmembers were initially asked to rate the wearability of the suit for 4-, 6-, and 8-hour time periods. After two crewmembers had already worn the ACES suit, it was decided that an additional question should be asked: “Could the crewmember wear the suit for 2 hours?” Data was collected then for 2-, 4-, 6-, and 8-hour wear time for all future runs. Only two ACES runs were not asked the question regarding the 2-hour time period.

Figure 6 through Figure 9 capture the wear time confidence and number of crewmembers that responded to each question. The x-axis shows the cumulative test time (e.g., T-start time plus xx minutes). The y-axis to the left shows the level of crew confidence from 1 (Not at all Confident) to 7 (Completely Confident). The y-axis to the right indicates the number of crewmembers responding favorably (e.g., said ‘yes they could wear it for the specified period’) to the question. The lines represent the average confidence of the crewmembers while wearing that suit for the specified wear time (e.g., 2 hours). Only crewmembers that responded favorably to the question are included in the average as opposed to weighting the unfavorable responses with a 0 value. Instead, the data presented show the number of crewmembers that responded favorably to wearing the suit for the specified time (e.g., 2 hours) as presented in the vertical bars. For example, a number of four would indicate that all four crewmembers thought one could wear the suit for the period of time although each crewmember’s individual confidence may differ as is reflected in the average confidence rating. Any differences from four should be seen as crewmembers stating the suit could not be worn for that period of time. The only exception to this is the 2-hour wear time for the ACES, as discussed earlier.

20. Do you think you could wear this suit for 4 hours in this position in a ground launch condition?

- ☐ Yes
☐ No

If yes,

	Rate the following:	Not at all Confident						Completely Confident
20a	Level of confidence that you could wear this suit in this position for 4 hours in a ground launch condition	1	2	3	4	5	6	7

Comments:

21. Do you think you could wear this suit for 6 hours in this position in a ground launch condition?

- ☐ Yes
☐ No

If yes,

	Rate the following:	Not at all Confident						Completely Confident
21a	Level of confidence that you could wear this suit in this position for 6 hours in a ground launch condition	1	2	3	4	5	6	7

Comments:

22. Do you think you could wear this suit for 8 hours in this position in a ground launch condition?

- ☐ Yes
☐ No

If yes,

	Rate the following	Not at all Confident						Completely Confident
22a	Level of confidence that you could wear this suit in this position for 8 hours in a ground launch condition	1	2	3	4	5	6	7

Comments:

23. Any other comments or suggestion you would like to make concerning the comfort of the suit?

Figure 5: Questions to Project Extended Wear

As one can see from Figure 6, any of the suits could be worn for a 2-hour period with a high degree of confidence. ACES was slightly higher than the two planetary suits in the pressurized condition; however, the discomfort was substantially higher in the same condition for the ACES suit (see Figure 4). This can be explained by the fact that ACES was the first suit worn and crewmembers were most familiar with the suit. Over the unpressurized condition, all three suits have the same confidence at the end of the test. Thus it is fair to conclude that all three suits could easily be worn for a 2-hour duration without complication.

At 4 hours (see Figure 7), the confidence decreases only slightly. In the pressurized condition, the number of crewmembers that felt they could wear the suit decreases; however, each crewmember agreed one could wear it for 4 hours in the unpressurized condition. At 6 hours (see Figure 8), the confidence decreases drastically and the number of crewmembers that said they could wear the suit for 6 hours also decreases. At 8 hours (see Figure 9), the number of crewmembers stating they could wear the suit for that time period falls once again, but the confidence increases minimally with the exception of the Mark III. In general, each crewmember was fairly confident for a period of 4 hours; however, their confidence began to wane at 6 hours.

Some crewmembers questioned whether it would ever be reasonable to even ask someone to sit for a period longer than 2 hours in the 1-g launch position. Research was conducted to determine the maximum amount of time crew sat on the pad during the Apollo missions. No data was found to define the minimum sit time on the launch pad. It was discovered that for Apollo 14 the crew went into a 40-minute hold pattern prior to launch. Likewise, the recent STS-114 timeline shows that the crew began entering the vehicle at T-3 hours; thus, it appears a minimum of 2 to 3 hours in a sitting position is likely for future CEV missions although this time will depend on the length of the launch window and planned checklist period.

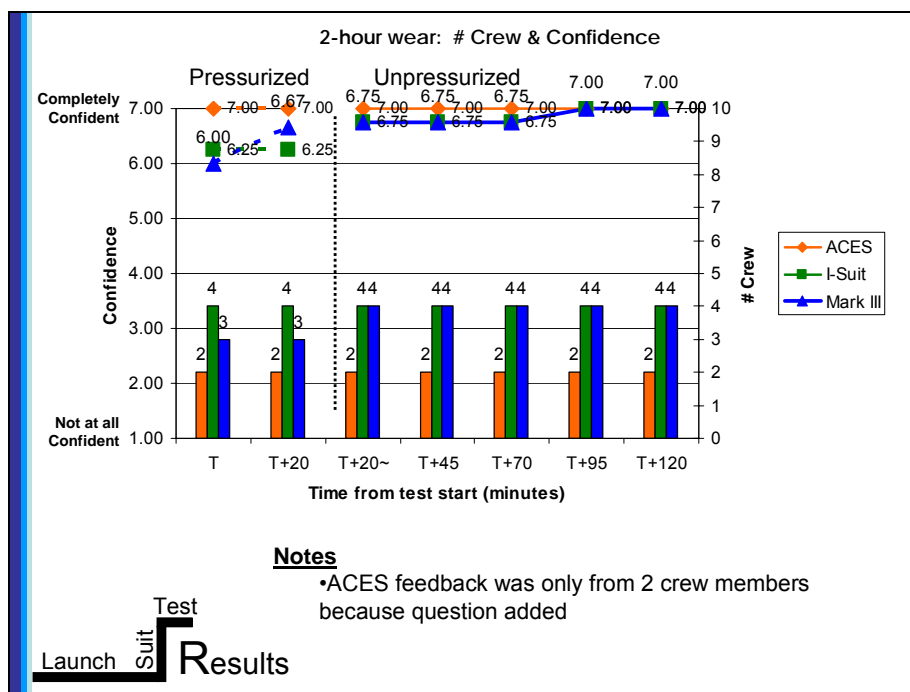


Figure 6: 2-hour Wear Confidence

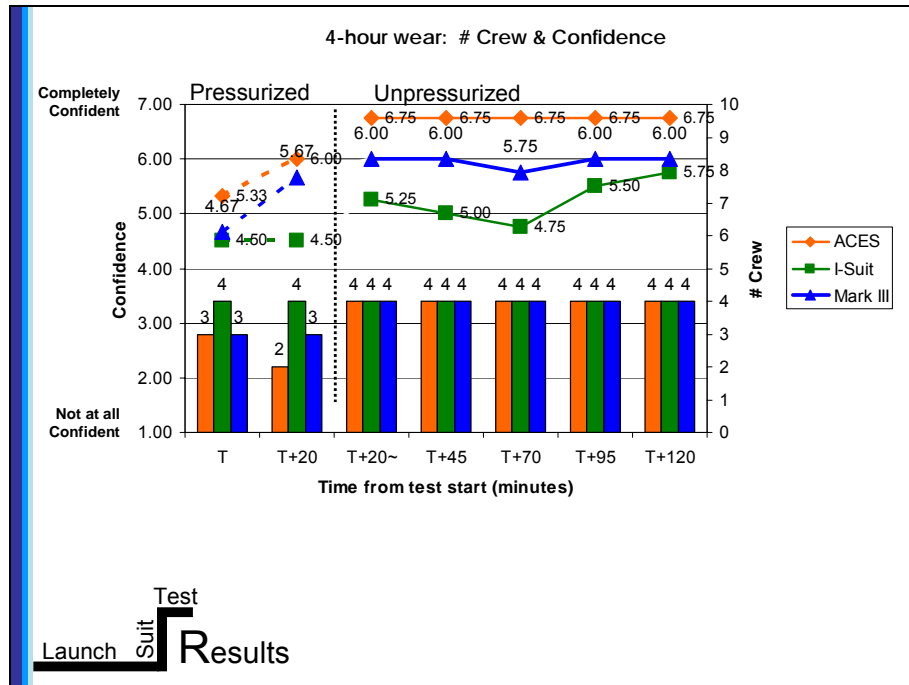


Figure 7: 4-hour Wear Confidence

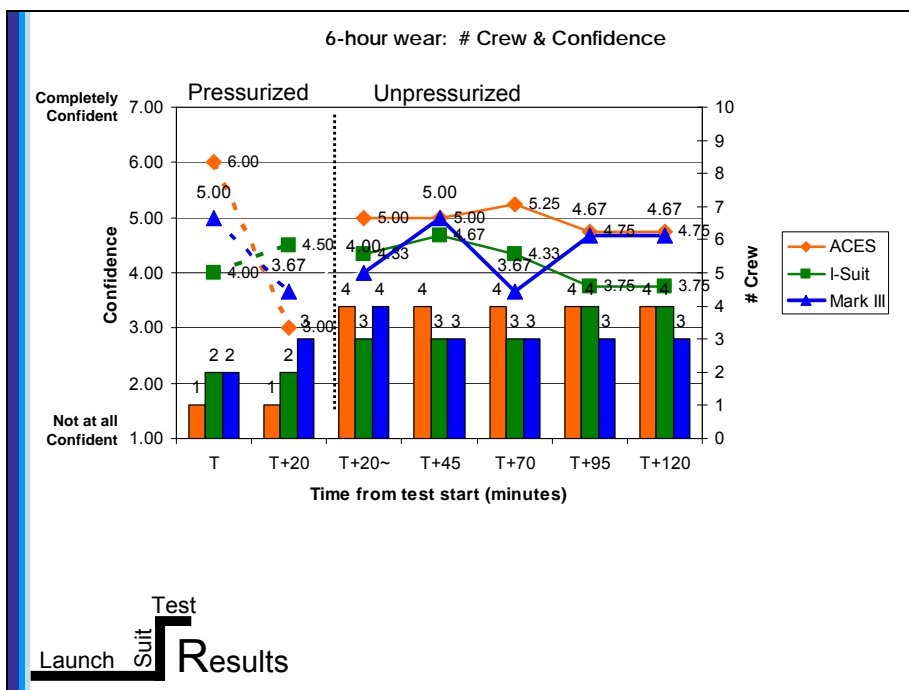


Figure 8: 6-hour Wear Confidence

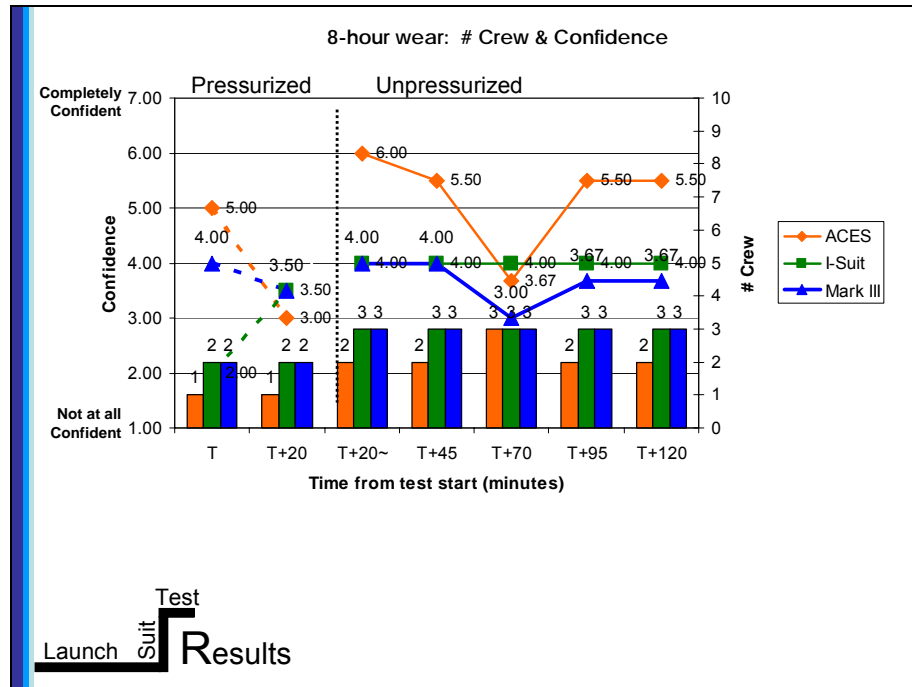


Figure 9: 8-hour Wear Confidence

5.1.2 Body Discomfort Scale Results

The second method used was the discomfort assessment scale (e.g., Borg scale) developed by Corlett et al. (1976). This scale (refer to Figure 10) allowed participants to indicate uncomfortable body parts and level of severity using an anatomical indicator. A value of 0 (zero) was assumed unless specifically reported by the crewmember. Like the holistic discomfort questionnaire, the discomfort scale was given twice (approximately every 20 minutes) during the pressurized portion of the test and five times (approximately every 20 minutes) during the unpressurized portion of the test.

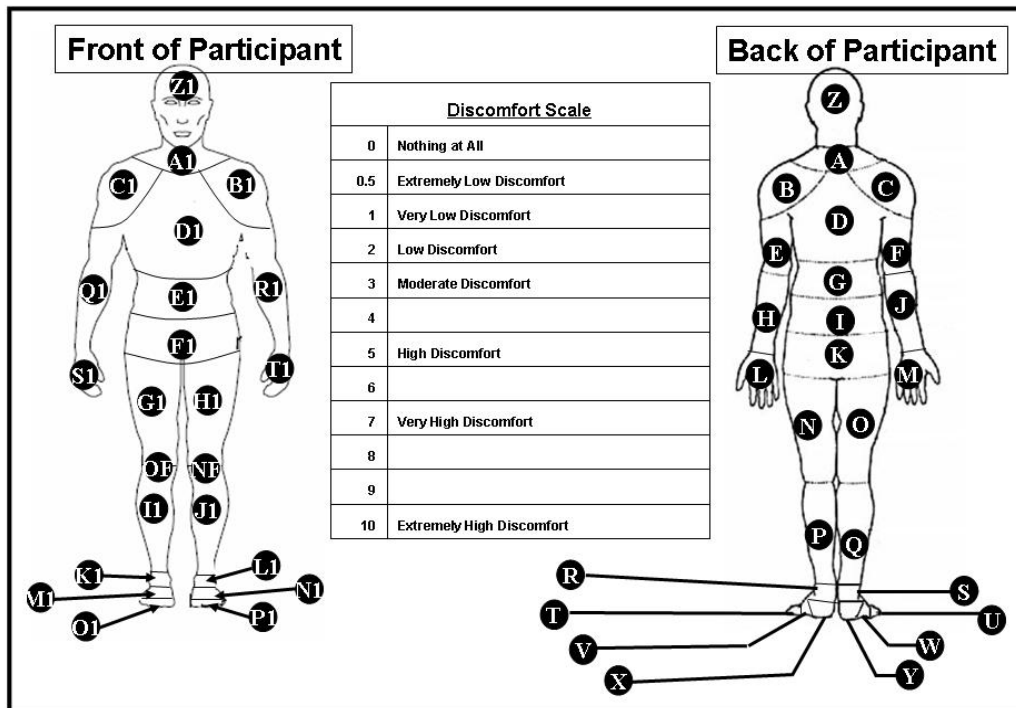


Figure 10: Body Discomfort Scale

5.1.2.1 Frequency of Reported Discomfort

Overall, 40 different anatomical areas, in both the pressurized and unpressurized conditions, were identified as experiencing some form of discomfort. Table 5 shows the number of anatomical areas that experienced some form of discomfort in each suit. It can be seen from this overview that the ACES had less reports of discomfort in the pressurized condition as compared to the other suits, yet, as discussed earlier, it had a higher level of discomfort at the end of the pressurized portion of the test (see Figure 4). In the unpressurized condition, no suit in general had more points of discomfort than any other suit and their average discomfort was similar (see Figure 4). What one can conclude from this data is that frequency of reports is not necessarily a direct indication of overall discomfort in a suit in and of itself.

In reality, a single point/area could cause a discomfort level that is unacceptable. For example, in the pressurized condition for the ACES, the discomfort rating was dominated by one area (e.g., popliteal fossa, feet). While discomfort did not reach its highest level in that condition, comments from crewmembers indicated if they had worn the suit much longer, pressurized, they would have likely stopped the test. Likewise it is reasonable to suggest that if a suit has a large number of points of discomfort, it might result in the same response from the wearer. In this test, no suit reached a frequency of reported discomfort points to warrant the wearer from stopping the test or reporting a high level of discomfort. From a design perspective, though, it is important to be aware that both situations, a single point of discomfort and many points of discomfort, can cause an uncomfortable situation.

Table 5: Identified Anatomical Areas and Level of Discomfort

Suit	Pressurized	Unpressurized
ACES	13	19
Mark III	17	23
REI-Suit	18	15

Figure 11 and Figure 12 show the percentage of reported anatomical regions with some level of discomfort for both the pressurized and unpressurized conditions, respectively. Percentages were used to account for the differences in discomfort queries (i.e., pressurized was queried twice, unpressurized was queried five times). Parts of the body or level of discomfort generally differed between the pressurized and unpressurized conditions. Table 6**Error! Reference source not found.** highlights the areas that had the most reports of discomfort (e.g., greater than 20% of reports) for both the pressurized and unpressurized conditions. Some areas reports did not change between the pressurized and unpressurized condition. For example, upper and lower arm had a high level of reports for the Mark III in both conditions. Likewise, in some instances, an area received high reports in only one of the conditions. While some areas had high reports of discomfort, as will be discussed later, some of these areas may have been eliminated with better design of the seat.

Table 6: Most Reported Anatomical Regions

Most Reported Anatomical Regions*		
Suit	Pressurized	Unpressurized
ACES	Head/neck Lower leg Feet	Head/neck Mid-region
Mark III	Upper arm Lower arm Lower leg	Upper arm Lower arm Shoulder Middle region Back
I-Suit	Shoulder Lower arm	Shoulder Back

Launch

Suit

Test

Results

* > 20% of reports

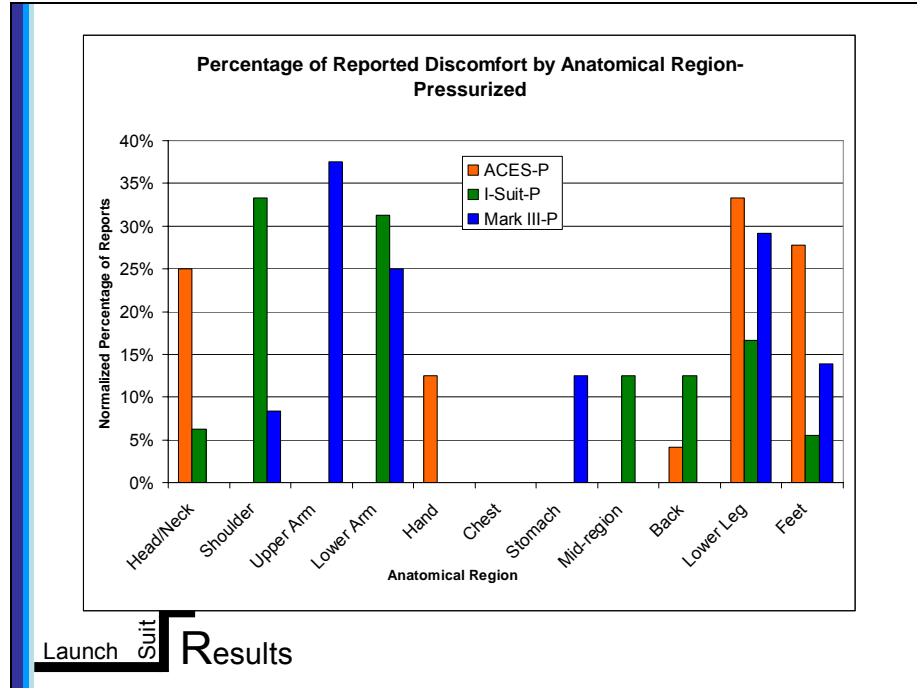


Figure 11: Percentage of Reported Discomfort by Anatomical Region-Pressurized

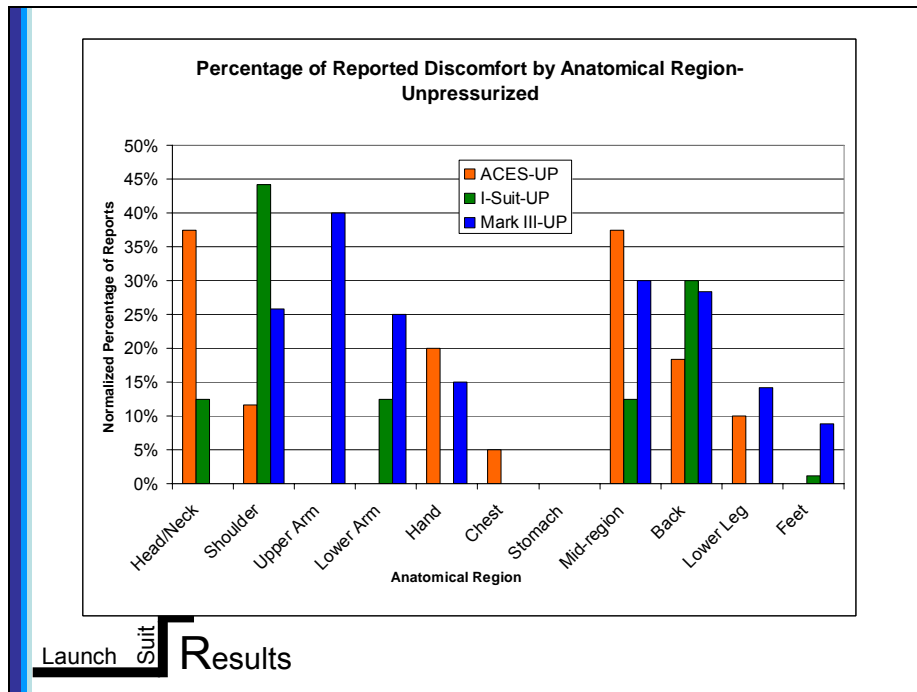


Figure 12: Percentage of Reported Discomfort by Anatomical Region-Unpressurized

5.1.2.2 Level (or Severity) of Discomfort

The previous discussion focused on the frequency of reported discomfort. This discussion will focus on the level of discomfort. Figure 13 and Figure 14 illustrate the level of discomfort for anatomical areas at the end of the test for a particular condition (i.e., at the end of 20 minutes for the pressurized condition and at the end of 100 minutes in the unpressurized condition).

Anatomical areas are only marked if they had an average discomfort level greater than or equal to 2 (Low), 3 (Moderate), and 5 (High) according to the Borg scale shown in Figure 10. In summary, the anterior anatomical areas had few points of discomfort. The posterior, as might be expected given the sitting posture (refer to Figure 1), had more points of discomfort.

In the pressurized condition, the REI-Suit had the most points of discomfort that exceeded a low level of discomfort (e.g., >2). The back, neck and knees had low levels of discomfort whereas the lower arms had moderate levels of discomfort. The shoulders had high levels of discomfort. The ACES and Mark III had minimal levels of discomfort in the pressurized condition with the exception of the back of the knees which experienced high levels of discomfort across all crewmembers in the ACES.

In the unpressurized condition, each suit experienced discomfort; however, no suit exceeded a moderate level of discomfort. Each suit experiences some low level of discomfort in the back region. The ACES had some low level of discomfort in the head and leg regions, as well. The REI-Suit had a high level of discomfort in the upper back, a moderate level in the hip region, and low level in the shoulders and midback region. The Mark III had moderate discomfort in the shoulders. Reports of discomfort in the shoulder area were caused by two primary factors: bearings and resting weight. The bearing tended to press on the participants in their underarm area of the shoulder. Likewise, because participants did not have arm support (e.g., arm rests), the weight of the arms tended to cause discomfort over time for the bearing enabled suits. Overall, the Mark III had the least level of discomfort in different regions of the body although it had a slight overall higher discomfort: 2.88 vs. 2.25 for ACES (refer to Figure 4).

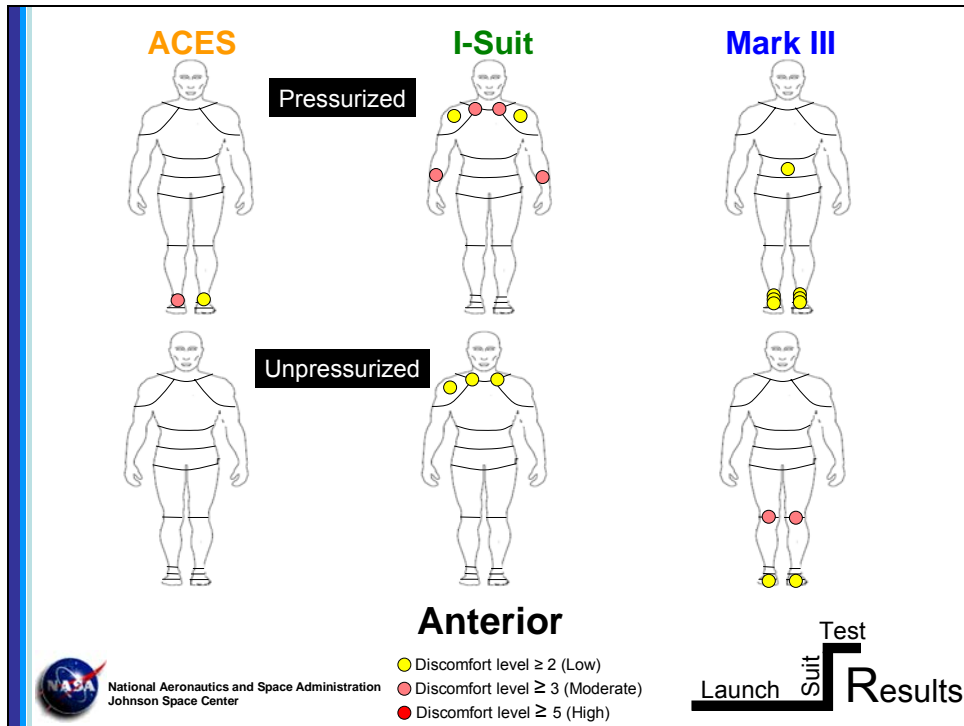


Figure 13: Anterior Discomfort Overview

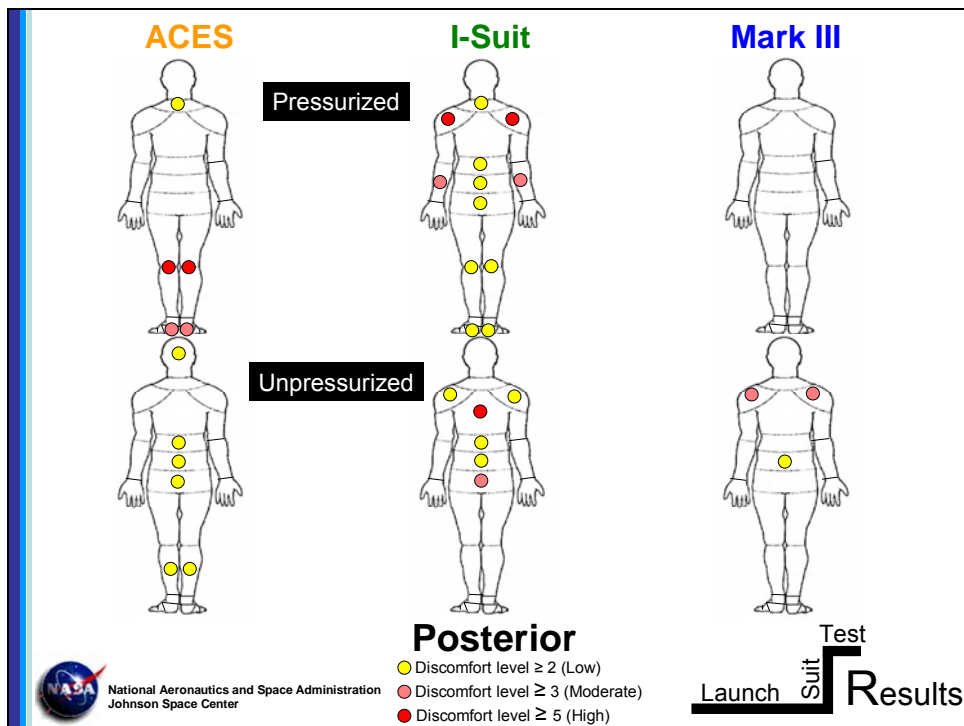


Figure 14: Posterior Discomfort Overview

5.1.2.3 Body Discomfort Results Details and Design Issues

For each anatomical area outlined in Figure 10, Appendix 2 details the level of discomfort over the test time period. All values are averaged across all four crewmembers. In general, 15 anatomical areas stood out as causing a noteworthy level of discomfort over time. These areas were identified based on the data that showed they exceeded a single instance of discomfort with a moderate level (3) or the discomfort increased over time (refer to Table 7).

Table 7: Greater than Moderate Discomfort Points

Body Part	Pressurized			Unpressurized			
	ACES	REI-Suit	Mark III	ACES	REI-Suit	Mark III	Design
Head (Posterior)	X						
Shoulder Strap (Right/Left)		X					¥
Shoulder (Right/Left Anterior)						X	¥
Shoulder (Right/Left Posterior)		X				X	¥
Forearm (Right/Left Anterior)		X					¥
Forearm (Right/Left Posterior)		X					¥
Hand (Left/Right)					X	X	
Upper Back					X		¥
Hips/Gluteus Maximus					X		
Knee (Left/Right)						X	
Popliteal Fossa (Left/Right)	X						
Instep (Right Anterior)	X						
Extensors (Right/Left)						X	
Heels (Right/Left)	X						
Toes (Right/Left)						X	
Total	4	4			3	6	
¥ - Elements that could have potentially been eliminated with addition of arm rests							

Figure 13, Figure 14, and Table 7 illustrate that while each suit experienced some level of discomfort, all could be potentially used as launch/entry suits. While some areas experienced moderate levels of discomfort, this discomfort can potentially be reduced with design changes. One limitation outlined was that the seat was a mock-up and did not encompass all the features of an actual seat. One of those features left out was the arm rests. Thus crewmembers were forced to support the weight of the suit arms while in the reclined position. While individual crewmembers enacted different strategies to temper this discomfort (e.g., put their thumbs in the suit waist ring to relieve weight), in reality these strategies were only slightly effective as evidenced by their level of discomfort. Thus Table 7 highlights areas of discomfort, as marked with a ‘¥’, that may have been reduced or even eliminated with the addition of features such as arm rests and lumbar support on the seat. Any future tests must consider seat design issues in creating a mock-up for testing.

5.1.3 Mobility Comfort Results

The third measure was a mobility comfort questionnaire, which sought out any discomfort the crewmember may have felt during movement (refer to Figure 15). This questionnaire was administered following each mobility assessment accomplished by the ABF laboratory. In all, the participant completed the questionnaire once during the pressurized condition and three times during the unpressurized condition.

	Rate the following:	No Discomfort						Extreme Discomfort
1.	Level of discomfort you felt when moving around	1	2	3	4	5	6	7

2. Did you experience any pinch points while moving around?

☐ Yes

☐ No

If yes, indicate where you experienced them and the level of discomfort?

See body chart

3. Do you feel you have limited movement ability relative to unsuited (rated) none at all to highly restricted?

☐ Yes

☐ No

If yes, indicate where you experienced them and the level of discomfort?

See body chart

4. Any other comments or suggestions you would like to make concerning the suit and mobility?

Figure 15: Overall Mobility Discomfort Questionnaire

Figure 16 shows the average mobility comfort response to question 1 of the questionnaire (Figure 15). As can be seen, in the pressurized condition, the Mark III was felt to be more comfortable while moving around. However, the REI-Suit and ACES were only marginally different from the Mark III. In the unpressurized condition, the ACES and REI-Suit were equally comfortable. The Mark III appears to increase the level of discomfort over time as compared to the other two suits. With regard to pinch points and mobility restrictions (refer to questions 2 and 3, Figure 16), two crewmembers experienced some pinch points and mobility restrictions at the elbows and shoulder areas in the Mark III. Table 8 details the crewmember comments with respect to mobility limitations and pinch points.

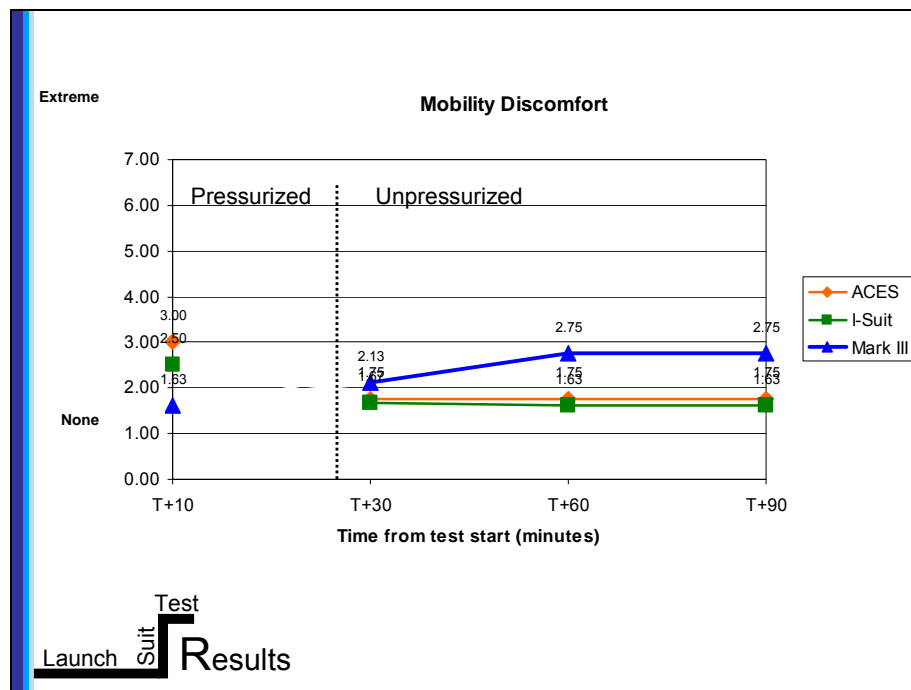


Figure 16: Mobility Comfort Questionnaire

Table 8: Crew Comments on Mobility Discomfort

Suit	Pressurized	Unpressurized
ACES	<ul style="list-style-type: none"> • All mobility limitations are at joints • Fingers had limited mobility as well • Not very mobile, close up ok, but harder as extend arms 	<ul style="list-style-type: none"> • Neck ring limited shoulder mobility • Neck ring causes suit to pinch when moving to head, noticed mainly on right side; felt better after relaxed • Limitations are in overhead mobility and across the chest
Mark III	<ul style="list-style-type: none"> • Mobility-can't bring knees in all way and can't roll trunk, thus crewmember can't extend reach by moving body; weight of butt on hip bearing pushes out hip bearing and spreads knees apart • Have to unlock joint to get to a single point (singularity); 85% of usual mobility; no way to move torso up; feel like a turtle on his back; might be able to use a hand hold to pull yourself up to do something; more comfortable than ACES pressure • Contact point when reaching across body; upper arm contacts suit which limits physical mobility-no discomfort; shield movement results in limited mobility –see video • Overall limited mobility; need to learn to work with the suit 	<ul style="list-style-type: none"> • Mobility-can't bring knees in all way and can't roll trunk, thus crewmember can't extend reach by moving body; weight of butt on hip bearing pushes out hip bearing and spreads knees apart • Rotating joints at elbows causes discomfort • Fatigue is causing movement discomfort • Singularities are issue; 88% of normal range of motion; like the ACES gloves better as that have better tactility • Pinch points at bicep/shoulder area; 88% mobility compared to shirt sleeve vs. 95% mobility with ACES compared to shirt sleeve • Sometimes hit singularities in different places; ideally – ACES arms for launch unpressure; Mark III arm for pressured • Fixed position limitations; easier in the unpressurized condition • Restricted mobility overall in arms/elbows • Contact with upper arm bearing caused increase in discomfort
REI-Suit	<ul style="list-style-type: none"> • Limited mobility; however, better than ACES • Elbow bearings or suit stiffness is reason for discomfort rating; shoulder joint gives full movement; elbow movement is limited; back of shoulder/elbow bicep at the joints pinch; because of joint programming, as you go through the transitions you get stuck; singularities are worse than Mark III • Limitations in shoulder/arms 	<ul style="list-style-type: none"> • Constraining; LCVG causing the constraint; LCVG is worse part of system • Very minor limitations at joint bearings • Run point-top back side of shoulder; pressurized movement – 70% of normal; unpressurized – 85% of normal • Limitations in shoulder/arms; arm lateral motion

5.1.4 *Postural Shifts Results*

A fourth measure, observed frequency of postural shifts, was considered. However, because the crewmembers were not properly instructed to emulate the launch posture for the entire 120-minute test period, accessing crewmember postural shifts was not deemed a reasonable evaluation. Review of the videotapes found crewmembers frequently discussing the suit with test evaluators and visitors. In these discussions, crewmembers frequently moved around to describe elements associated with the suit. Thus, because the proper controls were not in place for this test, it was decided that analysis of the video may draw improper conclusions with respect to crew comfort. Future tests should implement tighter controls to allow for such evaluations.

5.2 **Field of View – Objective 2**

The TRD/TPD initially called for the use of a panel grid lowered over the crewmember, that emulated the Goldman perimeter field of view test, to evaluate field of view (see Figure 17). In this test, the crewmember would have indicated how far along each radial they could see using labeled reference points. Because of facility limitations and conflict with other experimenter's apparatuses, a modified test was conducted to emulate the Goldman perimeter. This modified test conducted the same Goldman perimeter test except the experimenter was required to use a rod and ball at each radial to query the crewmember on when they could see the ball as it moved down the rod (see Figure 18 and Figure 19). This test format is similar to what is conducted in traditional eye exams where a physician moves an object in from the peripheral until a patient can detect the object. While this test allows for comparison between the three suits, the values should not be used for dictating requirements as the test measurement technique has not been fully validated. It does, however, allow for comparison testing, especially when comparing against an existing accepted suit design such as the ACES.

One should realize that this test assessed perceptual vision (e.g., detection of an object moving into our visual field). At the boundaries of our perceptual vision (e.g., field of view), objects lose their color and acuity. Thus, this test only tells us when a person saw an object entering their field of view and not whether they could read or appropriately recognize the color. Further testing would be required to establish the readable area boundaries which would be smaller than the perceptual vision boundaries.

For the pressurized condition, four radials were tested approximately at the 0-, 90-, 180-, and 270-degree locations with respect to the crewmember. Only four points were tested because of the limited time crewmembers were pressurized (i.e., 20 minutes). For the unpressurized condition, all sixteen radials, with 22.5 degrees between each radial, were evaluated. This covers the entire 360-degree vision field.

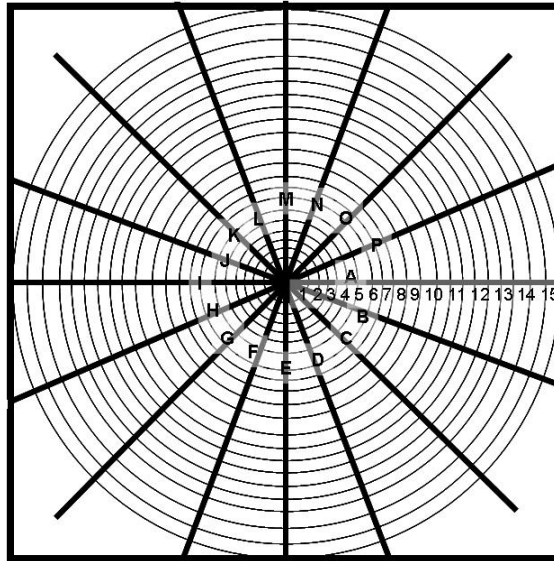


Figure 17: Goldman Perimeter

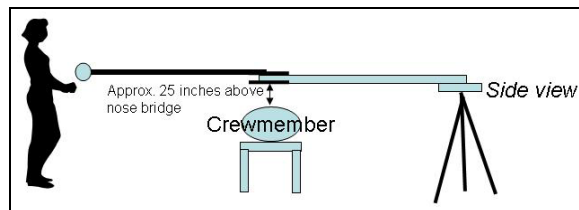


Figure 18: Modified Goldman Perimeter Field of View Test



Figure 19: Crewmember Participating in Field of View Test

5.2.1 Field of View Results

To evaluate the field of view, the minimum distance, average distance, and maximum distance seen by any single crewmember were evaluated. Each of these analyses found that, in the pressurized and unpressurized conditions, the planetary suits in general had equal or better field of view than the ACES. Figure 20 shows the average results in both the unpressurized and pressurized condition. The lines on the concentric circles show the field of view (in inches) in the unpressurized condition and the colored circles (at the 0-, 90-, 180-, and 270-degree locations) reflect the four points evaluated in the pressurized condition. While at some points one suit may have performed better than another suit, the differences were marginal. Thus, from a practical standpoint, one can consider it negligible given the limited number of participants run in the test.

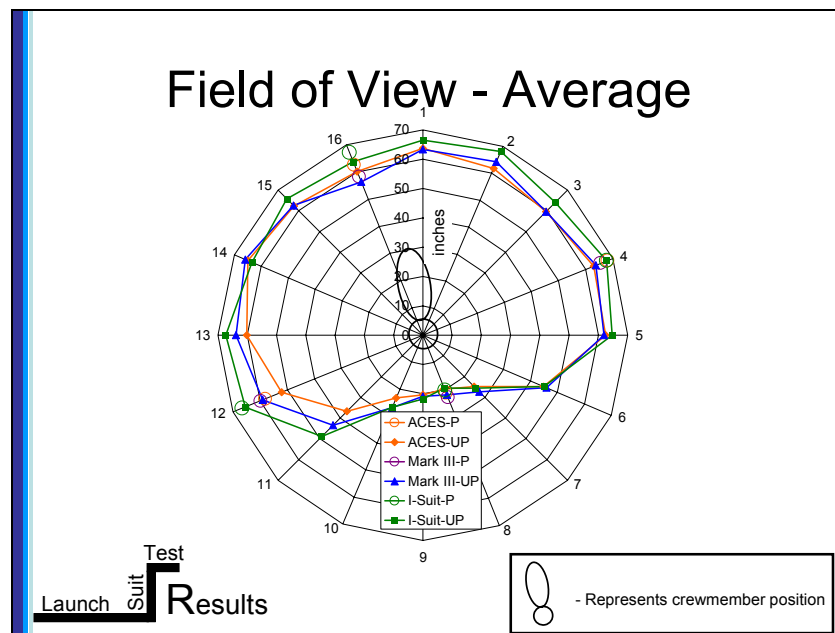


Figure 20: Field of View (Average)

5.3 Sit/Stand Ability – Objective 3

For this objective, at least one crewmember attempted to sit in the seat and get out of the seat in each of the different suits both pressurized and unpressurized. In all cases except ACES unpressurized, the crewmember was unable to fully sit or exit the seat without some form of assistance. Because of safety considerations and the fact that a crewmember was unable to complete almost all of the tasks in any of the suits unassisted, this portion of the test was concluded. Future tests will need to consider how crewmembers enter and exit a seat in the CEV without assistance, provided this is an eventual requirement.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The overarching question to be answered by this report is: “Should planetary suits be further considered for launch/entry suits?” In short, nothing was found during this test that would prevent one from considering planetary suits as an alternative to the current launch/entry type of suits.

For objective 1, three subjective measures of comfort were taken: a holistic discomfort questionnaire, body discomfort scale (Corlett and Bishop, 1976), and mobility questionnaire. With respect to overall discomfort, crewmembers experienced some discomfort in each suit. In the two planetary suits (i.e., Mark III, REI-Suit), the overall level of discomfort did not seem to differ much from the current ACES except during pressurization. Discomfort in the ACES during the pressurized condition dramatically increased during the 20-minute period and was substantially greater than the planetary suits.

The body discomfort scale looked at specific anatomical region discomfort, which varied by pressurization. The REI-Suit had the most anatomical points of discomfort that exceeded a low level of discomfort in the pressurized condition including the back, neck, knees, and lower arms. The shoulders had high levels of discomfort. The ACES and Mark III had minimal levels of discomfort in the pressurized condition with the exception of the back of the knees in the ACES. This area experienced high levels of discomfort across the crewmembers.

In the unpressurized condition, each suit caused some form discomfort; however, no anatomical region exceeded a moderate level of discomfort. Each suit experienced some low level of discomfort in the back region. The ACES had some low level of discomfort in the head and leg regions as well. The ACES head discomfort was primarily attributed to the pressure demand regulator. The REI-Suit had a high level of discomfort in the upper back, a moderate level in the hip region, and low level in the shoulders and midback region. The Mark III had moderate discomfort in the shoulders. Reports of discomfort in the shoulder area were caused by two primary factors: bearings and resting weight. The bearing tended to press on the participants in their underarm area of the shoulder. Likewise, because participants did not have arm support (e.g., arm rests), the weight of the arms tended to cause discomfort over time for the bearing enabled planetary suits. Overall, the Mark III had the least level of discomfort in different anatomical regions although it had a slight overall higher discomfort as compared to the ACES.

For mobility discomfort in the pressurized condition, the Mark III was felt to be more comfortable while moving around. However, the REI-Suit and ACES are only marginally different from the Mark III. In the unpressurized condition, the ACES and REI-Suit were equally comfortable. The Mark III appears to increase the level of discomfort over time as compared to the other two suits. Volume III will discuss mobility changes over time and crewmember comfort.

For objective 2, a test was conducted to emulate the Goldman perimeter, the gold standard for field of view assessment. Analysis of the field of view results found there were very few differences between the three suits in terms of visual field. There were only a few points where this was not the case. At those points where the ACES had better visibility, the margin was relatively small. Thus from a practical standpoint, one might consider it negligible given the

limited number of participants run in the test. Because of the measurement limitations (e.g., measurement technique, peripheral vision), these results are only useful for comparative analysis and should not be used to accomplish cockpit display design. Thus the visual field boundaries for which a crewmember can actually discriminate text, objects, and colors are less. Therefore, this data should only be used to highlight areas where one should be careful in locating displays. For example, Figure 20 illustrates that designing cockpit displays behind the head of a crewmember would create potential problems in seeing and interpreting the display. These visual boundaries also can change based on other factors (e.g., helmet configuration, vehicle configuration) and thus any cockpit display designs should take these factors into consideration.

In evaluating objective 3, one crewmember attempted to sit in the seat and get out of the seat in each of the different suits, both pressurized and unpressurized. For both planetary suits and the ACES pressurized, the crewmember was unable to fully sit or exit the seat without some form of assistance. Only in the ACES unpressurized was the crewmember able to enter and exit the seat without assistance. Because of safety considerations, this portion of the test was concluded. Several limitations existed in this test. First, this test only evaluated 1-g pad hold time operations and further testing is required to access other phases of operation. Second, a small sample (e.g., 4 crewmembers) was used for this test which is not representative of the entire crewmember core in terms of gender, anthropometric size, or other physical characteristics. Third, the test configuration, including the seat mock-up and suits, had constraints. The seat was not designed to allow for adjustability, and it did not include seat comfort factors such as arm rests. The planetary suits, while representative, may not be the actual suit designs and thus results from this test may not be fully extrapolated to all future suit designs. However, they are representative of the types of suits one would expect as possible suit designs.

In conclusion, the findings of this test support further study of the planetary suit for use as a potential launch/entry suit. The planetary suits evaluated for this test do not increase crewmember discomfort to a level greater than the current ACES and, in some cases, were found to be more comfortable than the ACES. In addition, the field of view was only marginally different in some zones and thus can be considered the same for the purpose of this test.

As a result of this test, several recommendations are made with regard to future tests, in general, and with respect to future tests that evaluate suit comfort including: (1) further testing of the planetary suits in other 1-g conditions is needed as indicated in Table 1; (2) a broader range of crew anthropometrics should be considered in future tests; (3) a more representative mock-up that is adjustable should be used for future tests; (4) during design of any new suits, tests should be performed to assess suit discomfort as well as other human performance elements (e.g., reach, field of view); and, (5) future tests should follow a strict protocol such as not to potentially influence the test.

7.0 REFERENCES

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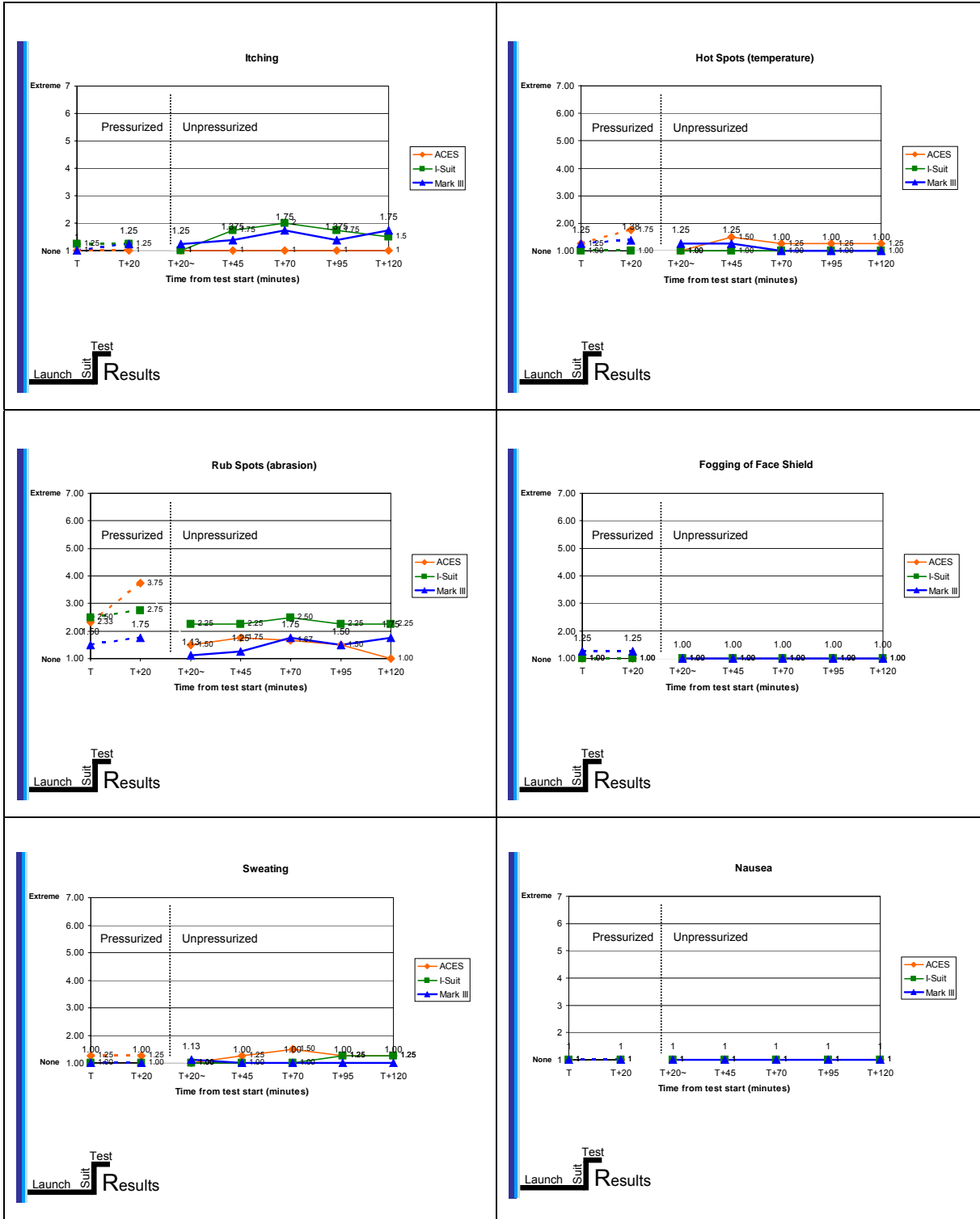
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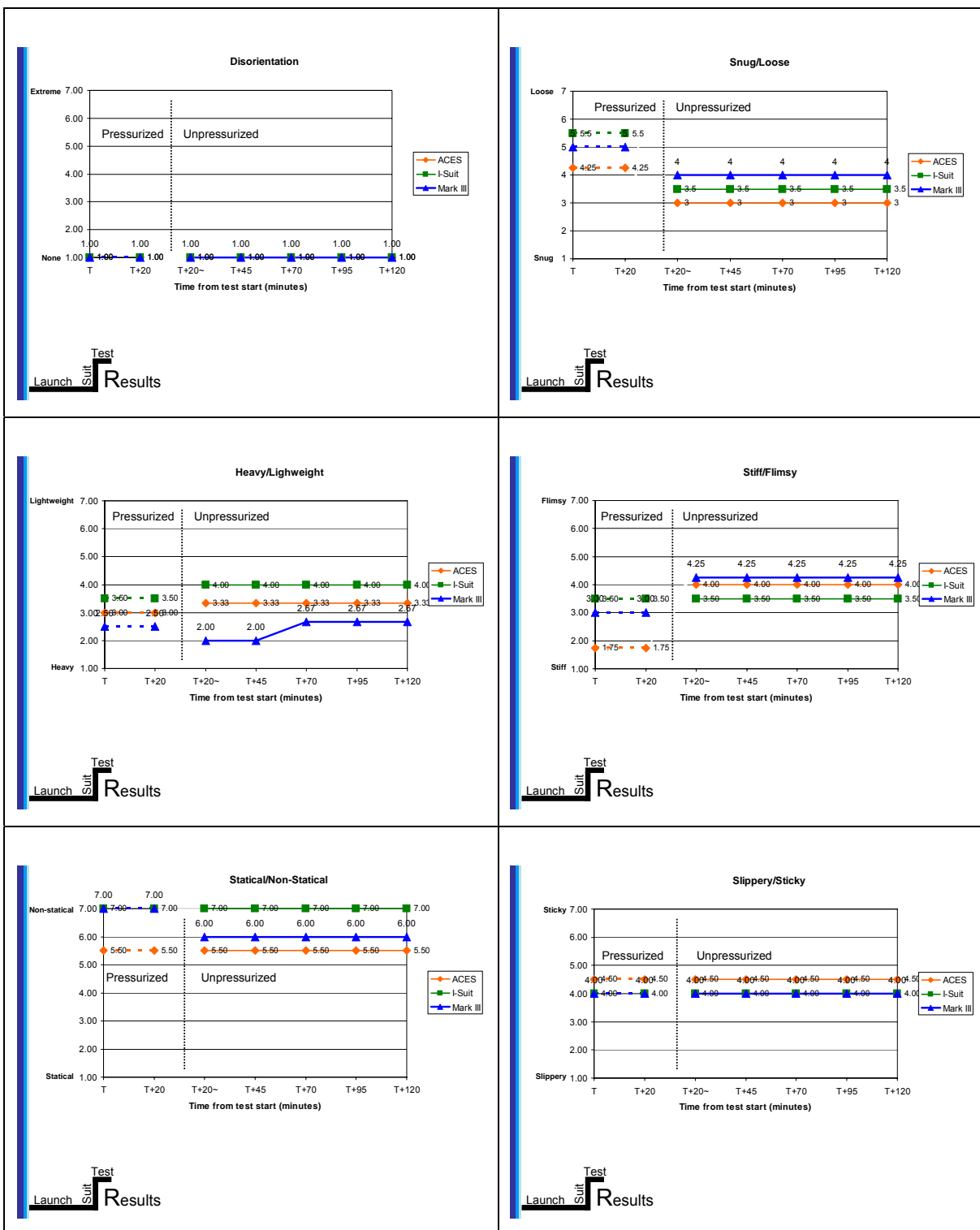
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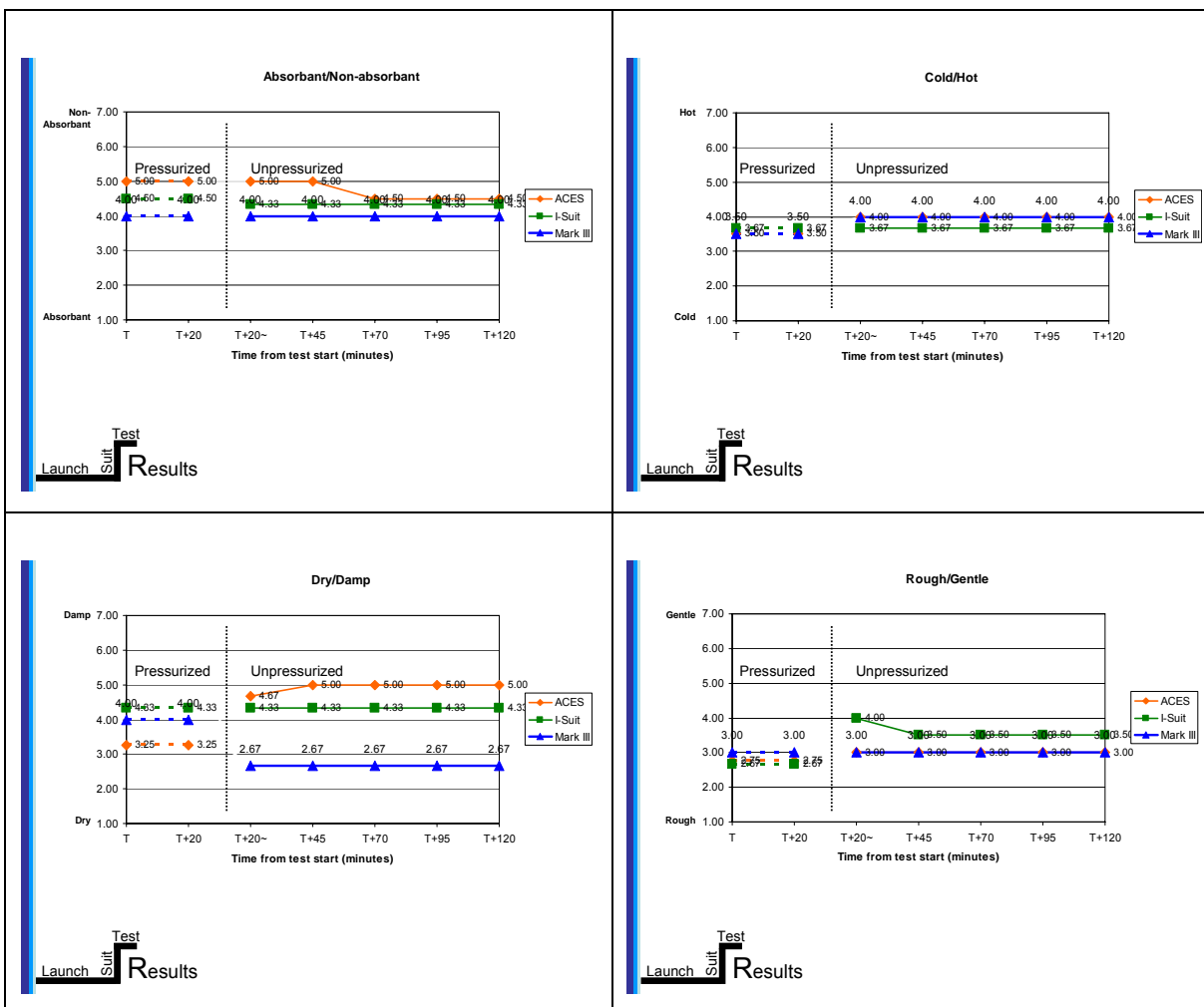
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8.0 APPENDICES

Appendix 1 Overall Discomfort Ratings

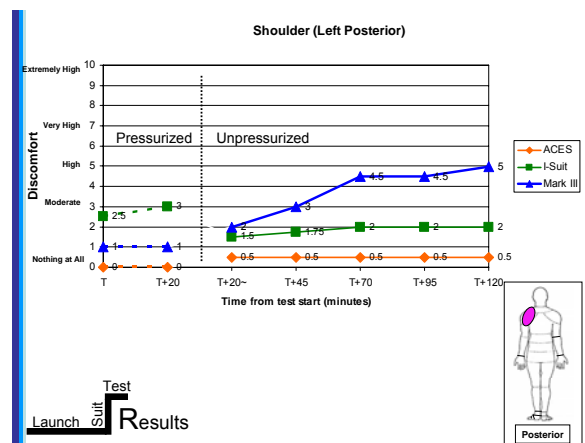
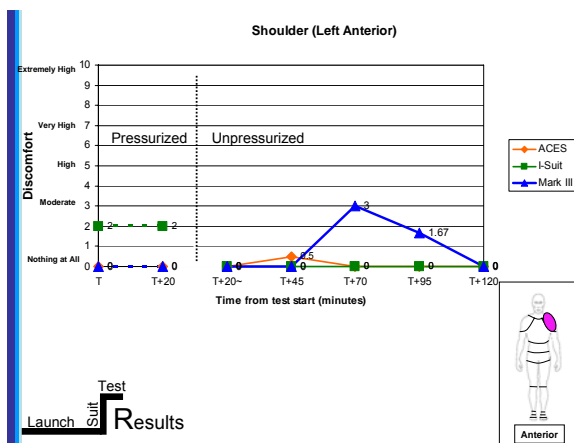
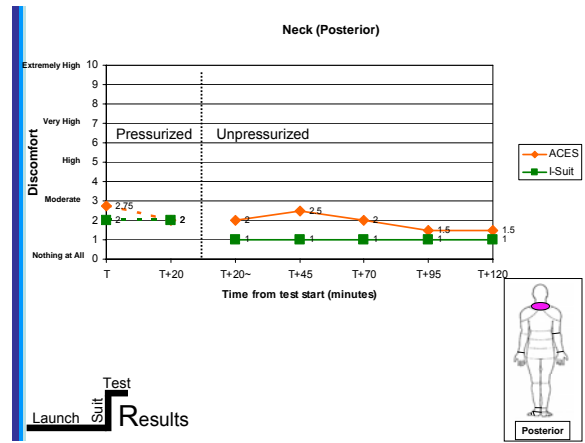
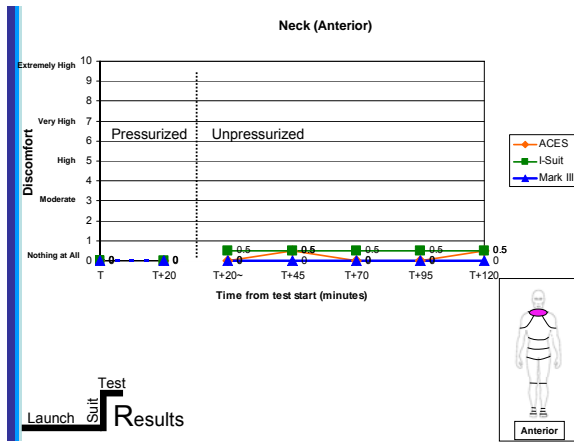
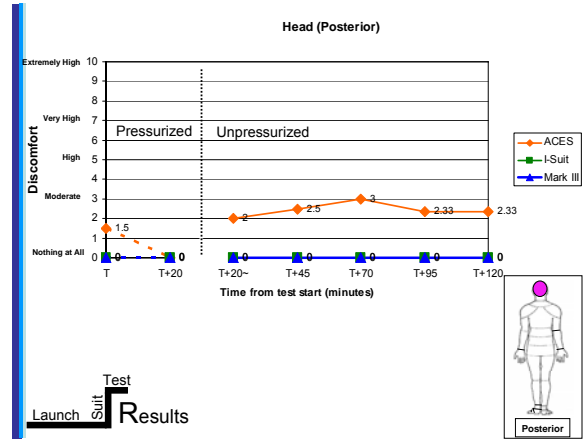
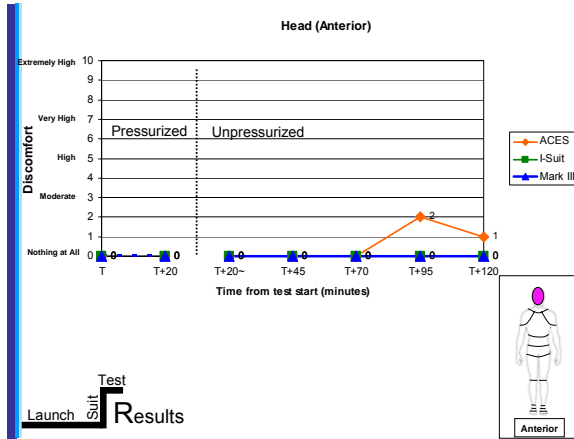


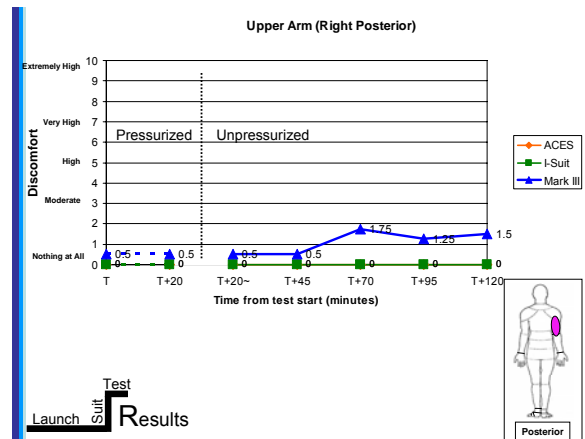
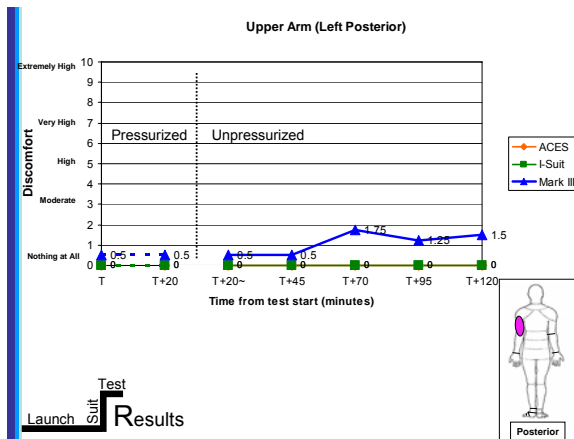
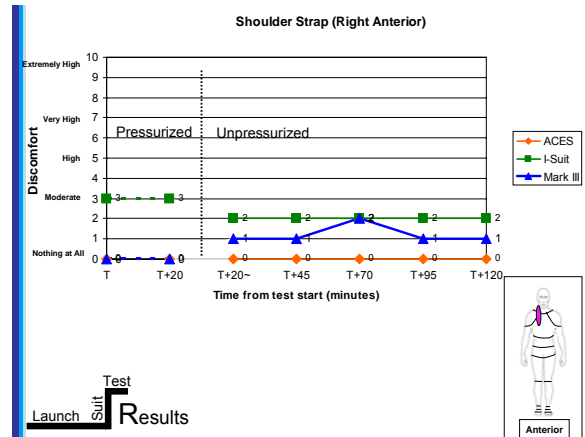
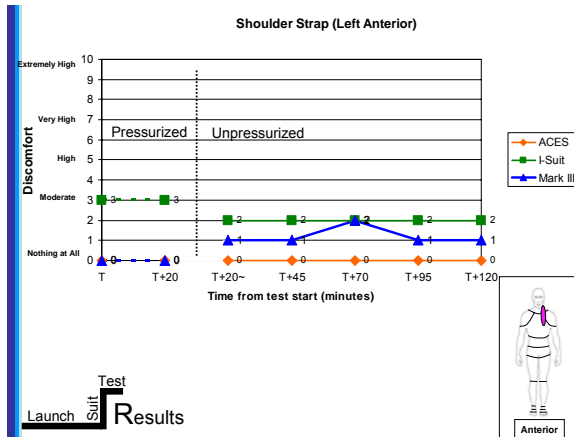
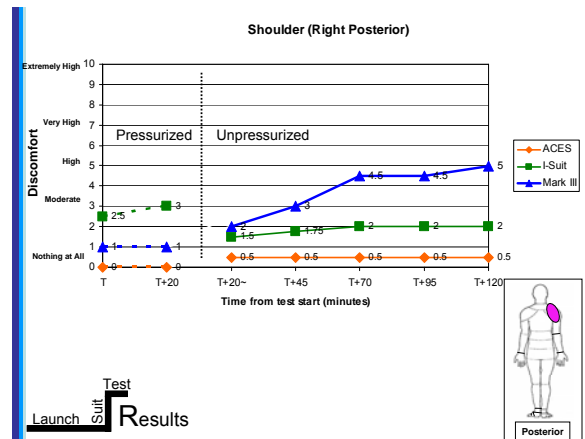
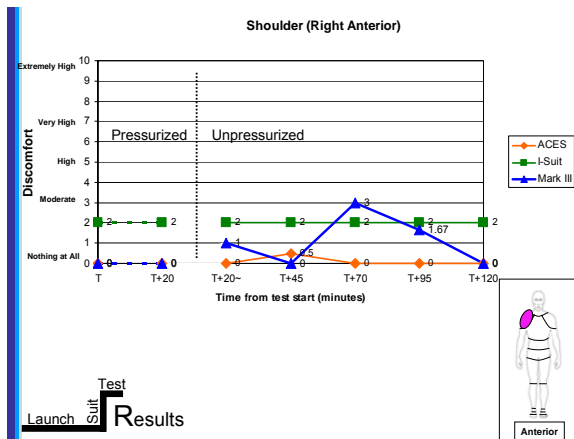


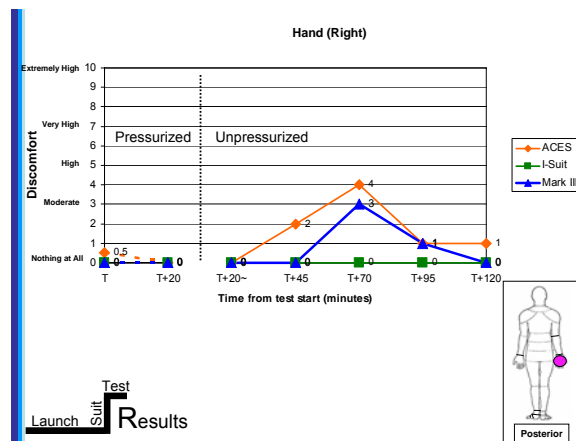
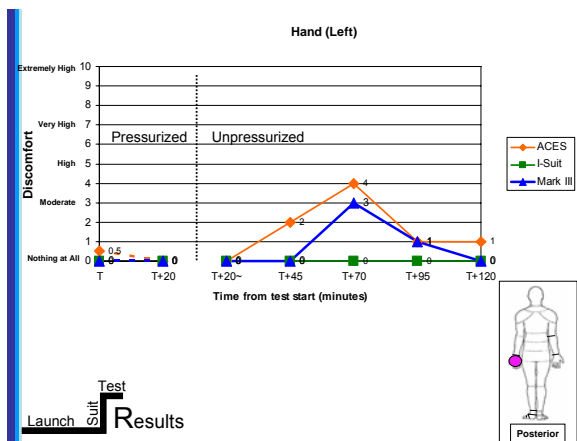
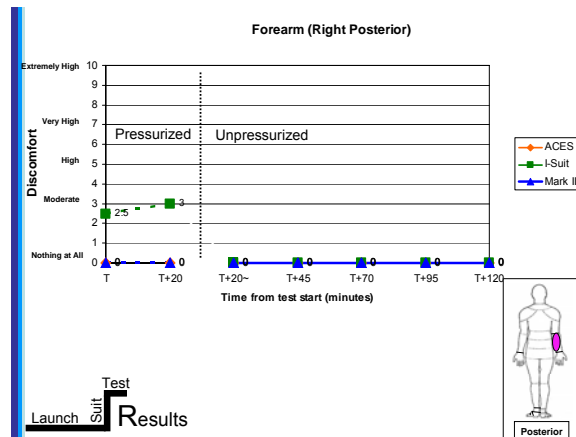
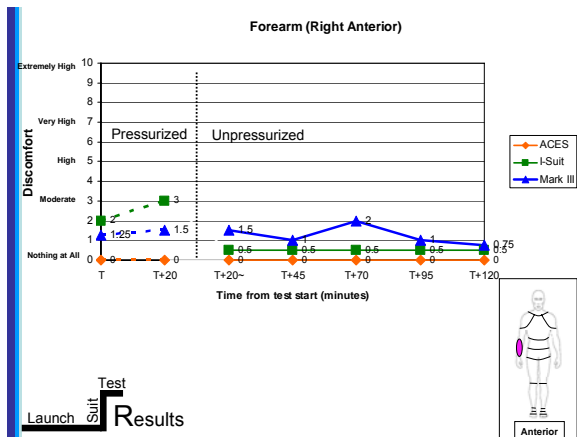
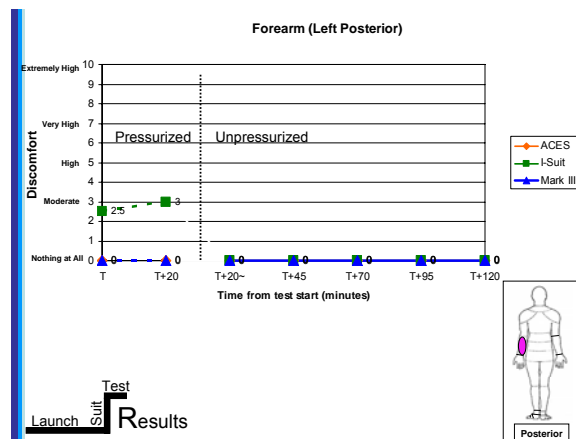
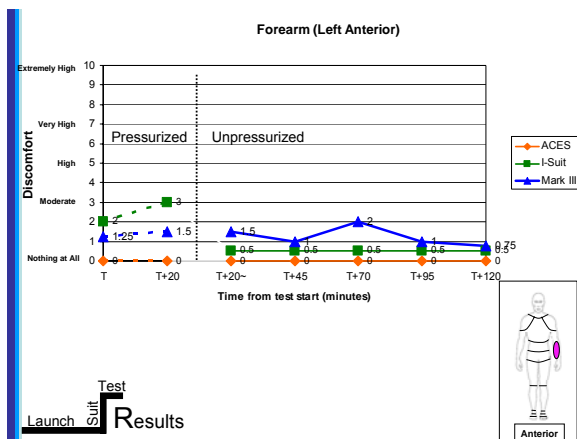


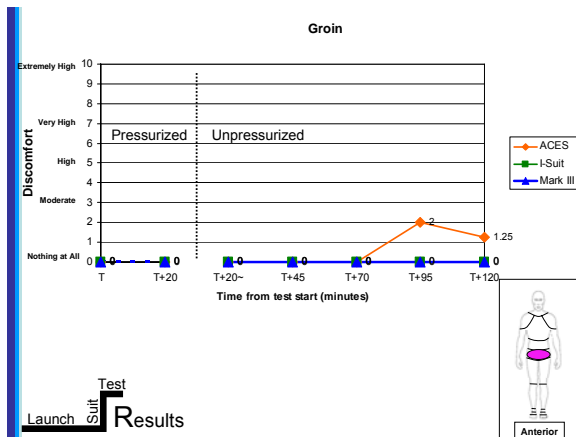
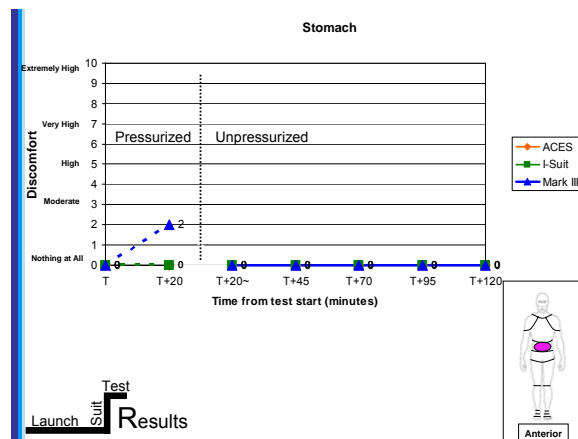
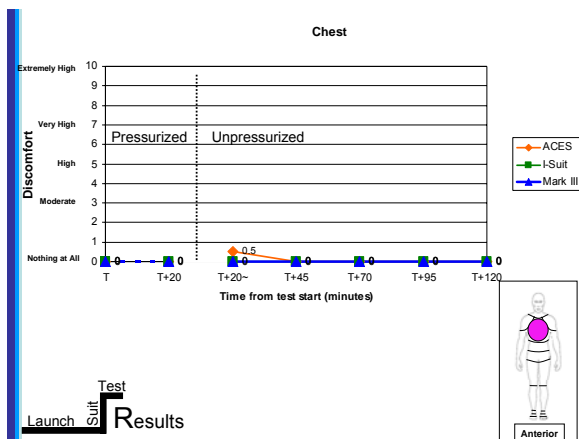
Appendix 2

Participant Identified Discomfort Ratings by Body Part

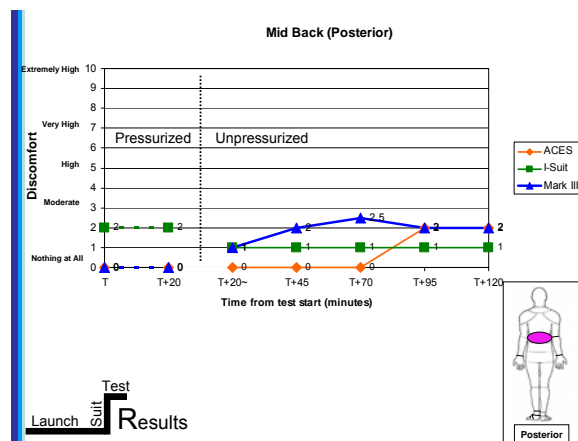
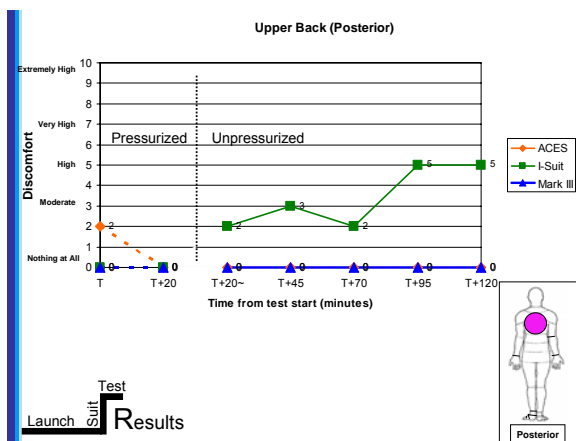


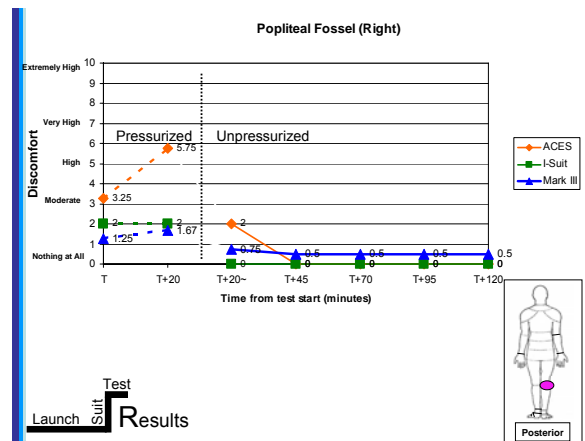
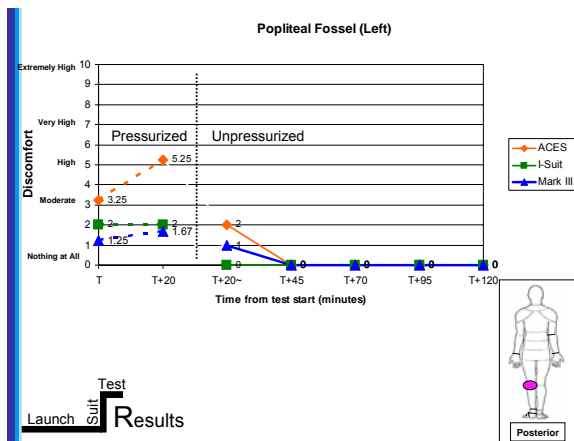
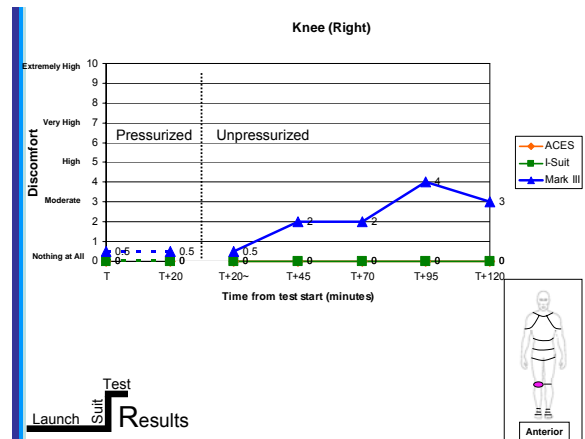
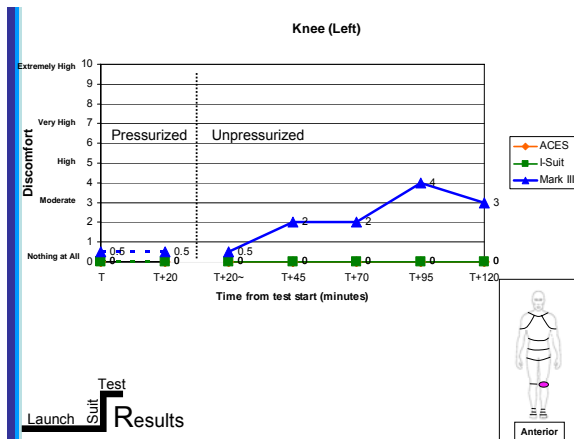
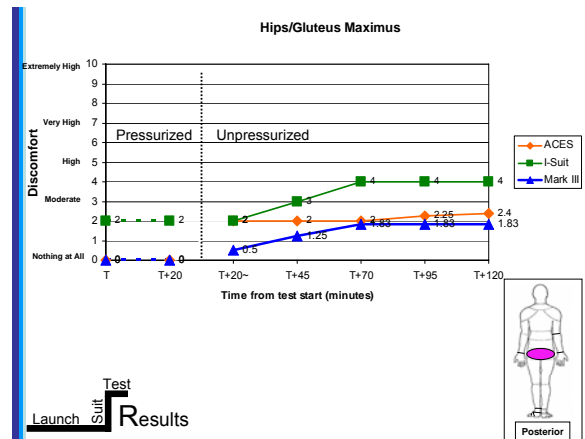
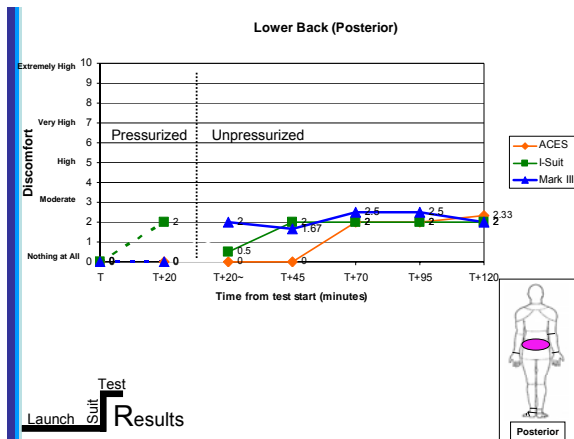


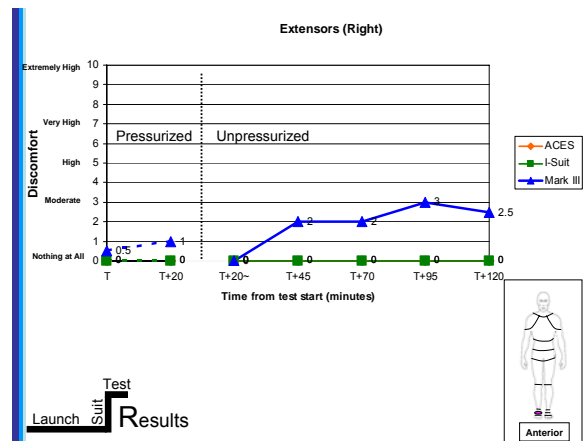
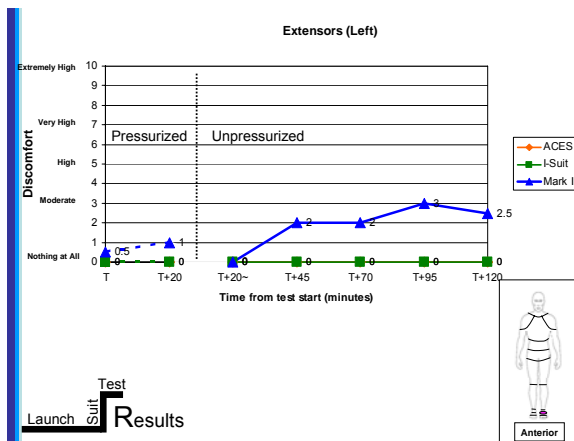
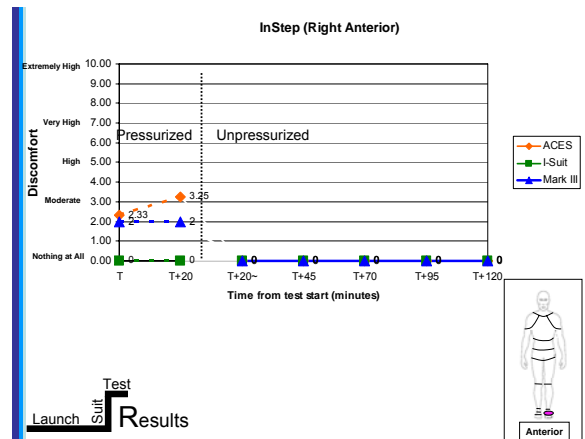
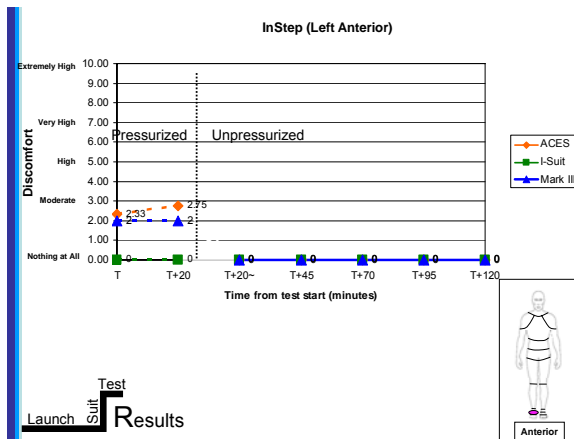
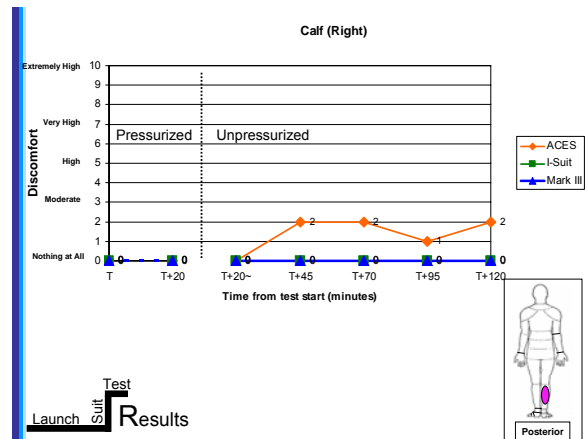
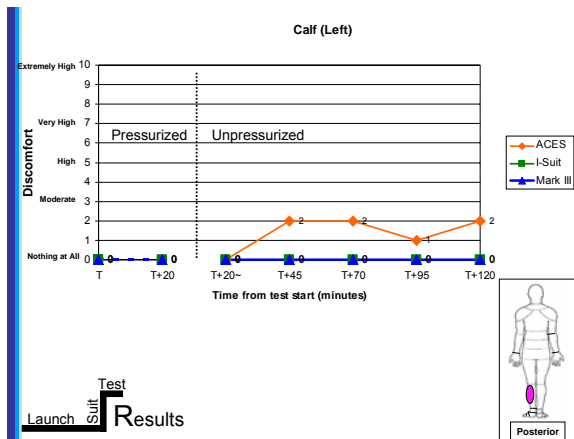


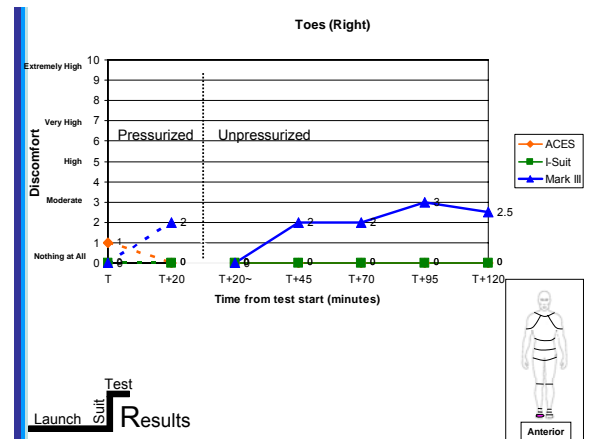
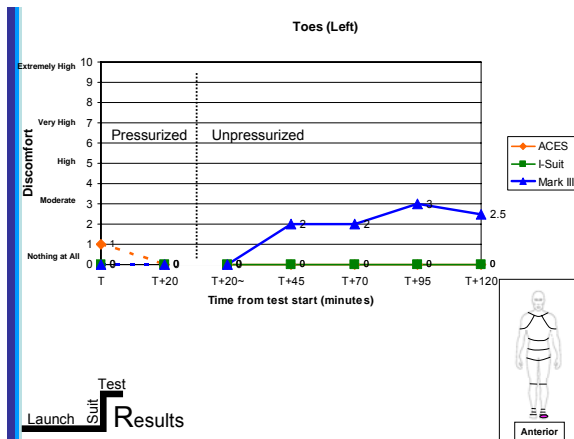
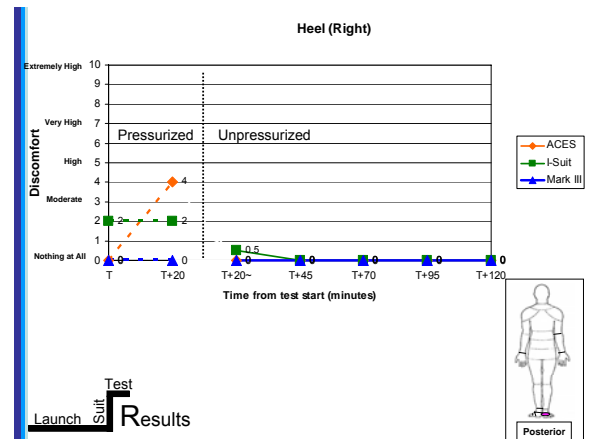
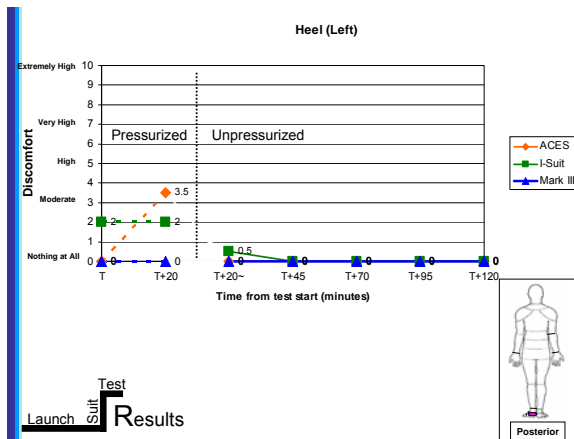


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Appendix 3

Anatomical Region Reported Discomfort

Body Region	Body Label	ACES		REI-Suit		Mark III	
		P	UP	P	UP	P	UP
Head	Head (Anterior)		15%				
	Head (Posterior)	25%	65%				
Shoulder/neck	Neck (Anterior)		15%		25%		
	Neck (Posterior)	75%	55%	25%	25%		
	Shoulder (Left Anterior)		10%	25%			20%
	Shoulder (Left Posterior)		25%	50%	95%	25%	25%
	Shoulder (Right Anterior)		10%	25%	25%		25%
	Shoulder (Right Posterior)		25%	50%	95%	25%	25%
	Shoulder Strap (Left Anterior)			25%	25%		30%
	Shoulder Strap (Right Anterior)			25%	25%		30%
Upper arm	Upper Arm (Left Posterior)					38%	40%
	Upper Arm (Right Posterior)					38%	40%
Lower arms	Forearm (Left Anterior)			25%	25%	50%	50%
	Forearm (Left Posterior)			38%			
	Forearm (Right Anterior)			25%	25%	50%	50%
	Forearm (Right Posterior)			38%			
Hands	Hand (Left)	13%	20%				15%
	Hand (Right)	13%	20%				15%
Chest	Chest		5%				
Stomach	Stomach					13%	
Mid-region	Groin		15%				
	Hips/Gluteus Maximus		60%	25%	25%		60%
Back	Lower Back (Posterior)		40%	13%	40%		55%
	Mid Back (Posterior)		15%	25%	25%		30%
	Upper Back (Posterior)	13%			25%		
Lower leg	Calf (Left)		25%				
	Calf (Right)		25%				
	Knee (Left)					25%	25%
	Knee (Right)					25%	25%
	Popliteal Fossel (Left)	100%	5%	50%		63%	5%
	Popliteal Fossel (Right)	100%	5%	50%		63%	30%
Feet	Arch (Left)					13%	
	Extensors (Left)					25%	20%
	Extensors (Right)					25%	20%
	Heel (Left)	25%		25%	5%		
	Heel (Right)	25%		25%	5%		
	InStep (Left Anterior)	88%				25%	
	InStep (Right Anterior)	88%				25%	
	Toes (Left)	13%					20%
	Toes (Right)	13%				13%	20%

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13. ABSTRACT (Maximum 200 words) The primary objective of the Launch Suit Test was to evaluate crewmember comfort in two planetary suit concepts during 1-g launch conditions similar to those to be experienced in the Crew Exploration Vehicle. This report addresses suit wear in a launch pad configuration; however, the overarching question is: "Should planetary suits be further considered for launch/entry suits?" The test plan outlined four objectives: assess crewmember comfort in the Advanced Crew Escape Suit (ACES), Mark III and the Rear Entry ILC Dover Suit (REI-Suit) in a recumbent position (with helmet); determine the visibility envelope of crewmembers while in the ACES, Mark III, and REI-Suit in a recumbent position (with helmet); determine the ability of crewmembers to sit and stand from a recumbent position unassisted while in the ACES, Mark III, and REI-Suit (with helmet); and determine the reach envelope and motion capability for the ACES, Mark III, and REI-Suit in a recumbent position (with helmet). This report addresses objectives 1 through 3. The findings support further study of the planetary suit for use as a potential launch/entry suit.				
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